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Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, Ohio

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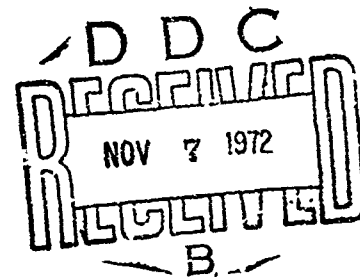
SUBSONIC PERFORMANCE POTENTIAL OF RAMJETS AND EJECTOR RAMJETS

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AIR FORCE AERO PROPULSION LABORATORY
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A method for analyzing the performance of a ramjet engine at subsonic flight speeds is presented. The absence of a known choked point (M=1) in the engine necessitates an iterative solution. A modified ideal gas analysis is utilized. Considered are the conventional ramjet with liquid fuel injection and an ejector ramjet using vaporized fuel injected into the engine at supersonic velocities. In the latter case, the fuel's momentum is significant and the ejector action draws additional air mass into the engine, which must be considered in the analysis. The method presented compares the two engine cycles at several subsonic flight speeds for both JP-4 and propane fuel. The effects of several levels of component efficiencies are considered.

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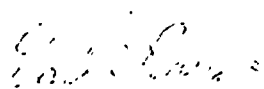
FOREWORD

This report was prepared by the Ramjet Applications Branch of the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The work described was accomplished under Task 301211, "Ramjet Design and Assessment," of Project 3012, "Ramjet Technology," and represents work accomplished from December 1970 to September 1971. The Project Engineer for this work was W. E. Supp.

This report was submitted by the authors January 1972.

This technical report has been reviewed and is approved.

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ABSTRACT

A method for analyzing the performance of a ramjet engine at subsonic flight speeds is presented. The absence of a known choked point (M=1) in the engine necessitates an iterative solution. A modified ideal gas analysis is utilized. Considered are the conventional ramjet with liquid fuel injection and an ejector ramjet using vaporizea fuel injected into the engine at supersonic velocities. In the latter case, the fuel's momentum is significant and the ejector action draws additional air mass into the engine, which must be considered in the analysis. The method presented compares the two engine cycles at several subsonic flight speeds for both JP-4 and propane fuel. The effects of several levels of component efficiencies are considered.

TABLE OF CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (CONTD)

SYMBOLS

SYMBOL	EXPLANATION
A	area, ft^2
A_c	inlet cowl area, ft^2
C_{DB}	burner drag coefficient
C_F	thrust coefficient, $F/q_o A_3$
C_{FN}	thrust coefficient with additive drag, $FN/q_o A_3$
C_P	pressure coefficient for diffuser
F	net internal thrust, lb_f
F_N	net internal thrust minus additive drag, lb_f
f/a	fuel-to-air mass ratio
g_c	conversion factor = 32.17405 lbm ft/lb_f sec^2
Isp	fuel specific impulse, $lb_f/lbm/hr$.
Isp_N	fuel specific impulse with additive drag, $lb_f/lbm/hr$.
$\dot{m}$	mass rate of flow, lbm/sec
M	mach number
M_N	molecular weight, $\dfrac{lbm}{lbm\text{-}mole}$
N_D	dump pressure loss exponent
P	pressure, lbf/ft^2
P_T	total pressure, lbf/ft^2
$\overline{P}$	stream thrust, lb_f
q_o	free stream dynamic pressure, lbf/ft^2
R°	universal gas constant = 1545 $\dfrac{ft\text{-}lbf}{lb_m\text{-}mole - {}^\circ R}$
T	temperature, ${}^\circ R$
T_T	total temperature, ${}^\circ R$

SYMBOLS (CONTD)

SYMBOL	EXPLANATION
(ΔT_T) actual	combustor actual total temp. rise, °R
(ΔT_T) ideal	combustor ideal total temp. rise, °R
u	velocity, $^{ft}/sec$
X	X functic
Y	Y function	See Section III
Z	Z function
γ	ratio of specific heats
η_c	combustion efficiency = (ΔT_T) actual$/(\Delta T_T)$ ideal
ρ	density; $^{1bm}/ft^3$

SUBSCRIPTS

0 - 5	engine stations (see Figures 1 and 2)
P	ejector ramjet primary chamber
*	ejector ramjet primary nozzle throat
C	ejector ramjet primary nozzle exit
T	total conditions

SECTION I

INTRODUCTION

The purpose of this report is to analyze the performance of two ramjet engine cycles operating at subsonic flight conditions. One is a conventional liquid-fueled ramjet and the other is an ejector ramjet that uses gaseous propane. Both JP-4 and liquid propane conventional ramjets are considered. The ejector ramjet introduces its fuel at supersonic velocities with a momentum high enough that it might increase the cycle pressure ratio and overall engine performance over that obtainable in the conventional ramjet. The magnitude of this performance is determined on an ideal cycle basis.

In this report, three types of engines are analyzed (see Table I): (1) a propane-fueled ejector ramjet; (2) a propane-fueled ramjet; and (3) a JP-4-fueled ramjet. Several efficiency levels for each type of engine are considered.

First, each engine is assumed to have no internal losses such as burner drag, combustion efficiency losses, diffuser losses, or friction losses. These results establish the basic trends and serve to determine the maximum values possible for the performance variables. This "no loss" case is referred to as the ideal case.

Secondly, component efficiencies are applied equally to all three engines. Baseline values of these component efficiencies were considered to be representative state-of-the-art values for a subsonic, JP-4

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fueled ramjet engine; values used were a burner drag coefficient of 4.0
and a combustion efficiency of 90%. These results establish practical
performance estimates for the JP-4 ramjet and compare them with those of
propane-fueled engines having equal component efficiencies.

Instead of using a burner drag coefficient, we applied another
efficiency factor to the ejector ramjet. Since the ejector ramjet uses
the dump into the combustion chamber as the flame-holding device and
does not have a baffle type flameholder, the burner drag of 4.0 was
replaced with an estimated dump loss correction based on experimental
results (Reference 5). Since the ejector ramjet has a diffuser section
ahead of the dump, experimental corrections (References 3 and 4) were
applied to the flow to account for this diffuser loss.

Most of the above mentioned parametrics were computed assuming
variable inlet size and, therefore, do not consider additive drag
effects. Several select cases have been corrected for additive drag
to demonstrate the order of magnitude of the additive drag correction.
The same exit-to-combustor-area ratio of 0.55 is used for all three
engines.

A computer program was written to calculate the performance of these
engine cycles. The method is described in Section III. Appendixes I
and II describe the computer program.

TABLE I

CYCLES INVESTIGATED

CYCLE	COMPONENT LOSSES
PROPANE-FUELED EJECTOR RAMJET	
Cycle 1	No Losses
Cycle 2	$C_{D_B} = 4$ and $\eta_c = 90\%$
Cycle 3	$C_p = 0.51$, $N_D = 0.25$ and $\eta_c = 90\%$
PROPANE-FUELED RAMJET	
Cycle 1	No Losses
Cycle 2	$C_{D_B} = 4$ and $\eta_c = 90\%$
JP-4-FUELED RAMJET	
Cycle 1	No Losses
Cycle 2	$C_{D_B} = 4$ and $\eta_c = 90\%$

SECTION II

DESCRIPTION OF CYCLES

1. THE RAMJET CYCLE

The conventional ramjet engine has been described and analyzed many times in the literature, and this baric treatment will not be repeated here. The majority of these treatments consider the ramjet at supersonic flight speeds with a choked exit nozzle, which presents a convenient station to begin analysis. The ramjet operating at subsonic flight speeds, however, usually has no choked station throughout the entire engine. Figure 1 presents a schematic of such an engine and defines the engine station nomenclature. A convergent nozzle is usually employed and, since the internal flow is entirely subsonic, pressure changes at any station are felt throughout the engine. The mass flow entering the engine will adjust itself, generally, so that the static pressure at the exit (Station 5) is equal to the ambient pressure. There are a few cases at high subsonic flight speeds where Station 5 can be choked with $P_5 > P_0$.

For the purposes of this analysis, an ideal inlet was considered so as to facilitate the presentation of data in parametric form. Also, no capture area was specified. Therefore, ideal one-dimensional flow is considered between Station 0 and Station 3. The results thus present the net jet thrust coefficient. A known capture area can be imposed and the data presented can be corrected for additive drag between Station 0 and Station 1. This was done for selected cases to describe the method.

Component losses can be considered if desired. Total pressure losses due to friction or flameholders in the combustor are defined by a burner drag coefficient, to be defined in the next section. A combustion efficiency based on burner ideal total temperature rise can be specified, if desired. The nozzle is considered ideal and no losses are defined. Fuel is considered to be injected at room temperature. The fuel mass is considered in the continuity equation, but its momentum is neglected.

The analysis procedure was chosen to facilitate rapid calculation and convergence on digital computer facilities. Component efficiencies, engine geometries, fuel/air ratio, and flight conditions are assumed. An initial estimate of the free stream area (or mass flow) is made and the properties at each station throughout the engine, from Station 0 to Station 5, are calculated. The static pressure at Station 5 is compared with the ambient static pressure of the known flight condition. These must be equal for a practical solution (except for the one exception where the exit nozzle is choked). If these pressures do not match, the estimated value of A_0 is modified and the calculations are repeated. When this matching of static pressures has been achieved, the engine performance parameters (thrust coefficient and specific impulse) are calculated.

2. THE EJECTOR RAMJET CYCLE

The analysis of the ejector ramjet is similar to that of the ramjet except in the treatment of the fuel addition. A schematic of the ejector ramjet is shown in Figure 2. A fuel injector in the form of a primary rocket with a C/D nozzle is located at Station 1. Fuel is heated to vaporization and is then introduced into the primary. This

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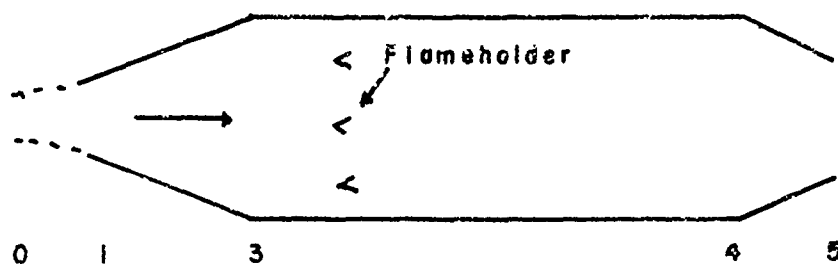
Figure 1. Ramjet Engine
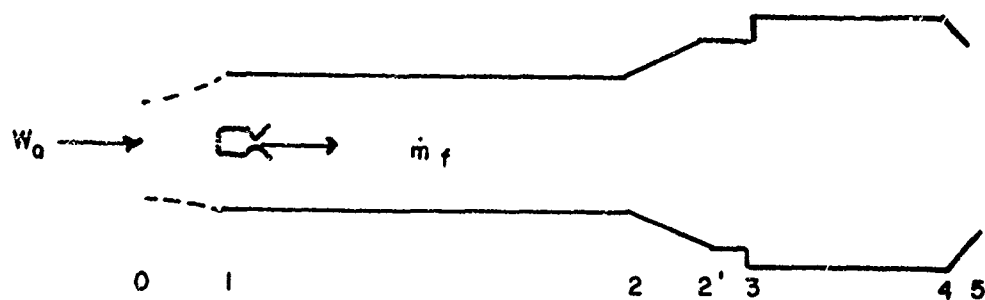
Figure 2. Ejector Ramjet Engine

fuel is gaseous at high pressure and elevated temperature. The fuel
expands in the C/D nozzle at supersonic velocities, with a momentum
significantly high to be considered in the cycle. The fuel and air mix
between Stations 1 and 2 without burning. The mixed stream then enters
the combustor through a diffuser and sudden dump. This area change serves
as a flameholding device to sustain combustion. The rocket primary
acts as an ejector and draws additional air into the engine. The momentum
of the primary increases the cycle total pressure ratio over that of a
conventional ramjet.

Component losses through the engine can be considered in two ways.
A burner drag coefficient can be applied to correct for all pressure
losses, as was done for the conventional ramjet. The losses associated
with the diffusion and sudden dump can be considered separately as a
function of the geometry with correlations to be described in the next
section. A combustion efficiency based on the burner ideal total
temperature rise can be specified if desired. Incomplete mixing of the
fuel and the air in the mixing tube will result in less ejector action
and less mass flow through the engine than the ideal case.

A provision is incorporated to account for these estimated losses.
The method chosen is to arbitrarily reduce the primary momentum by some
percentage to obtain a reduced pressure level at the end of the mixing
tube (Station 2). This method was chosen for ease in computer programming
and results in a converged air mass flow less than that obtained from the
ideal ejector ramjet but still more than that possible from the conventional
ejector ramjet at the same condition. The component losses can be applied to

the degree necessary to reduce ideal ejector performance to the level
corresponding to actual test data. Mixing losses were not considered
in the study results presented in this report.

SECTION III

ANALYSIS PROCEDURES

1. GENERAL

The ramjet and ejector ramjet cycles can be analyzed using constant gamma, ideal gas equations. It is a requirement for subsonic engines that the pressure at the exit of the nozzle be equal to the free stream pressure. It is therefore the purpose of the cycle analysis to find the air flow through the engine which will allow the nozzle exit pressure to match the free stream pressure for the given engine parameters. To calculate the nozzle exit pressure, it is necessary to calculate the Mach number and pressure at each station of the engine beginning at the inlet. There is one exception to the above criteria. If the nozzle is choked the exit pressure can be greater than or equal to ambient pressure

The Mach functions X, Y, and Z will be used to simplify the analysis procedure in this report. The following is a brief discussion of these functions. The equations of continuity, and momentum and energy are used to relate the conditions at one engine station to another. The continuity equation in its simplest form states that the mass flow rate at Station i is equal to the mass flow rate at Station i+1. This is written

$$\dot{m}_i = \dot{m}_{i+1} + \dot{m}_{added} \qquad (1)$$

Using the ideal gas law $\rho = \dfrac{P M_w}{RT}$

and the following relationships

$$\dot{m} = \rho A V$$

$$\frac{T_T}{T} = 1 + \frac{\gamma-1}{2} M^2$$

$$\frac{P_T}{P} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

Equation 1 can be written

$$\frac{P_T A M}{\sqrt{T_T}} \sqrt{\gamma \left(1 + \frac{\gamma-1}{2} M^2\right) \frac{\gamma+1}{1-\gamma}} \sqrt{\frac{g_c M_w}{R}} \Bigg]_i$$

$$= \frac{P_T A M}{\sqrt{T}} \sqrt{\gamma \left(1 + \frac{\gamma-1}{2} M^2\right) \frac{\gamma+1}{1+\gamma}} \sqrt{\frac{g_c M_w}{R}} \Bigg]_{i+1}$$

$$+ \dot{m} \text{ added}$$

This equation is simplified by defining

$$X = M \sqrt{\gamma \left(1 + \frac{\gamma-1}{2} M^2\right) \gamma+1 / 1-\gamma}$$

This gives the final form of the continuity equation

$$\left[\frac{P_T A X}{\sqrt{T_T}} \sqrt{\frac{g_c M_w}{R}}\right]_i = \left[\frac{P_T A X}{\sqrt{T_T}} \sqrt{\frac{g_c M_w}{R}}\right]_{i+1} + \dot{m} \text{ added} \qquad (2)$$

The momentum equation for a frictionless, constant area duct is

$$\left[\frac{\dot{m} u}{g_c} + PA\right]_i = \left[\frac{\dot{m} u}{g_c} + PA\right]_{i+1}$$

This equation can be expanded in a manner similar to the continuity
equation to give

$$\left[P_T A Z\right]_i = \left[P_T A Z\right]_{i+1} \tag{3}$$

where Z is defined as

$$Z = \frac{1 + \gamma M^2}{(1 + \frac{\gamma-1}{2} M^2)} \frac{\gamma}{\gamma-1}$$

The quantity $P_T A Z$ is called stream thrust and is denoted by the symbol $\bar{P}$.
If the continuity and momentum equations are combined, the following
equation is obtained

$$\bar{P} = \frac{\dot{m} \sqrt{\bar{T_T}}}{\gamma} \sqrt{\frac{R}{g_c M_w}} \tag{4}$$

where

$$Y = \frac{x}{z}$$

Equations 2, 3, and 4 are used to calculate the flow conditions through
the inlet. A complete explanation of these equations is given in
Reference 2. The Mach number functions X, Y, and Z are used to determine
the Mach number.

In this study, all engine areas and the fuel/air ratio are assumed
known, as well as the free-stream temperature, pressure, and Mach number.

The ideal temperature rise in the combustor, the molecular weight, and the gamma at the exit of the combustor are tabulated as a function of the air total temperature and the fuel/air ratio. Values of combustor efficiency, η_c, and burner drag coefficient, C_{DB}, were assumed to permit us to evaluate their effect on engine performance.

The combustion efficiency is defined as

$$\eta_c = \frac{(\Delta T_T)_{actual}}{(\Delta T_T)_{ideal}}$$

The burner drag coefficient is defined as

$$C_{DB} = \frac{\overline{P_3} - \overline{P_4}}{\frac{1}{2} \gamma_3 A_3 M_3^2 P_3}$$

where the term $\bar{P}_3 - \bar{P}_4$ is the drag loss caused by the flameholder.

2. RAMJET ANALYSIS

The ramjet analysis consisted of the following: First we assumed an inlet capture area. Then we used the continuity equation to calculate the conditions at the entrance to the combustor, and the momentum and continuity equations to calculate the conditions at the exit of the combustor. Finally, we used the continuity equation to relate the condition at the exit of the combustor to the conditions at the exit of the nozzle.

The method of analysis is as follows:

(a) Assume an A_0.

(b) From continuity, calculate the Mach number at Station 3. Assuming the inlet isentropically diffuses the air and the value of gamma at both stations is 1.4, then

$$X_3 = X_0 \frac{A_0}{A_3}$$
$$M_3 = f(X_3)$$

(c) Calculate the free-stream total pressure.

$$P_{TO} = P_0 \left(1 + \frac{\gamma_0 - 1}{2} M_0^2\right)^{\frac{\gamma_0}{\gamma_0 - 1}}$$

Since isentropic diffusion has been assumed in the inlet, it follows that

$$P_{T3} = P_{TO}$$

(d) Calculate the mass flow rate of air

$$\dot{m}_A = P_0 A_0 M_0 \sqrt{\frac{\gamma_0 \ g_c \ M_{wo}}{R \ T_0}}$$

(e) From the given fuel/air ratio, calculate the fuel flow rate.

$$\dot{m}_f = \dot{m}_A \ f/a$$

(f) Calculate the Mach number at Station 4 from the continuity and momentum equations.

$$Y_4 = \frac{Y_3}{1 + f/a} \sqrt{\frac{Mwo}{Mw_4} \left[1 + \eta_c \frac{(T_{T4} - T_{T6})}{T_{To}} \right]} \frac{1 + \gamma M_3^2}{\left[1 + \gamma M_3^2 \left(1 - \frac{1}{2} C_{DB} \right) \right]}$$

$$M_4 = f(Y_4)$$

(g) Calculate the total pressure at Station 4 from the momentum equation.

$$P_{T4} = P_{T3} \left[\frac{z_3}{z_4} - \frac{1}{2} C_{DB} \frac{\gamma_2 M_3^2}{z_4} \frac{P_3}{P_{T_3}} \right]$$

(h) Calculate the Mach number at Station 5 from the continuity equation. It is assumed that the values of gamma, total temperature, and total pressure at Station 5 are the same as those at Station 4.

$$X_5 = X_4 \frac{A_4}{A_5}$$

$$M_5 = f(X_5)$$

(i) Calculate the static pressure at Station 5.

$$P_5 = \frac{P_{T_4}}{\left(1 + \frac{\gamma_4 - 1}{2} M_5^2 \right)^{\gamma_4 / \gamma_4 - 1}}$$

(j) Compare the static pressure at Station 5 with the ambient pressure P_0. If these pressures do not compare reasonably well, adjust A_0 and return to Step b. If

$$P_5 > P_0, \text{ increase } A_0$$

$$P_5 < P_0, \text{ decrease } A_0$$

Once the pressures have be $\lrcorner$ satisfactorily matched, the engine performance can be calculated.

(k)   Thrust = $\quad P_{T4}\, A_5\, Z_5 - P_{T0}\, A_0\, Z_0 - P_0\,(A_5 - A_0)$

$\quad\quad\quad$ Isp = thrust/$\dot{m}_f$

Note: If the Mach number at any station exceeds one, reduce A_0 and return to Step (b). If the Mach number at Station 5 equals one and $P_5 \geq P_0$, this is a solution.

3.   EJECTOR RAMJET ANALYSIS

The ejector ramjet was analysed in a manner similar to the ramjet. In addition to burner drag and combustion efficiency, ejector effectiveness, diffuser and dump loss were also considered. Integration of the ejector into the ramjet cycle analysis is the only major deviation from the previous analysis.

The method of analyzing the ejector ramjet is as follows:

(a)   Assume a value for A_0.

(b)   From the continuity equation, calculate the Mach number at Station 1, assuming the inlet isentropically diffuses the air, and the value of gamma at both stations is 1.4.

$$X_1 = X_0\, \frac{A_0}{A_1}$$

$$M_1 = f\,(X_1)$$

(c)   Calculate the free stream total pressure

$$P_{T0} = P_0\left(1+ \frac{\gamma_0 - 1}{2}\, M_0^2\right)^{\frac{\gamma_0}{\gamma_0 - 1}}$$

Since isentropic diffusion has been assumed in the inlet, it follows that

$$P_{TI} = P'_{To}$$

(d) Calculate the air stream thrust at Station 1 from the momentum equation.

$$\bar{P}_{A_I} = P_{To} \, A_I \, Z_I$$

(e) Calculate the mass flow rate of air.

$$\dot{m}_A = P_o \, A_o \, M_o \sqrt{\frac{\gamma_o \, g_c \, M_w}{R \, T_o}}$$

(f) From the given fuel/air ratio, calculate the fuel flow rate.

$$\dot{m}_f = \dot{m}_A \; f/a$$

(g) Calculate the total pressure of the fuel injector assuming a choked throat. In this analysis the ejector geometry is fixed; therefore, the ejector total pressure is varied to match the flow rate.

$$P_{TP} = \frac{\dot{m}_f}{A_* X_*} \sqrt{\frac{T_{Tf} \, R}{g_c \, M_w}}$$

where A_* = area of injector throat

X_* = X function at throat

T_{Tf} = total temperature of fuel

(h) Calculate the Mach number at the exit of the injector.

$$X_e = \frac{X_* \, A_*}{A_e}$$

$$M_e = f\,(X_e)$$

(i) Calculate the stream thrust at the ejector exit.

$$\ddot{P}_e = P_{TP} \, A_e \, Z_e$$

(j) Calculate the temperature, molecular weight, and gamma of the mixed fuel and air at Station 2 by mass averaging the individual properties. The individual physical properties are obtained from tables of data or empirical correlations.

(k) Calculate the stream thrust at Station 2 from the momentum equation. For the ideal case

$$\bar{P}_2 = \bar{P}_i + \bar{P}_e$$

If it is desired to account for inefficiency of the ejector action, a component efficiency can be incorporated. For example

$$\bar{P}_2 = \bar{P}_i + \eta \, \bar{P}_e$$

(l) Calculate the Mach number at Station 2, from the continuity and momentum equations.

$$Y_2 = \frac{\dot{m}_A \, \dot{m}_f}{F_2} \sqrt{\frac{T_{T2} \, R}{g_c \, M_{w_2}}}$$

$$M_2 = f \, (Y_2)$$

(m) Calculate the total pressure at Station 2 from the momentum equation.

$$P_{T2} = \frac{\bar{P}_2}{A_2 \, Z_2}$$

(n) Calculate the static pressure at Station 2.

$$P_2 = P_{T2}(1 + \frac{\gamma_2 - 1}{2} M_2^2)^{\frac{\gamma_2}{1-\gamma_2}}$$

(o) Calculate the static pressure at Station 2' if diffuser losses are to be considered

$$P_2' = (\frac{1}{2} \bar{C}_p \gamma_2 M_2^2 + 1) P_2$$

where $\bar{C}_p$ is an experimentally determined diffuser loss factor obtained from References 3 and 4. If isentropic diffusion is assumed

$$P_2' = P_2$$

(p) Calculate the Mach number at Station 2' using the continuity equation.

$$M_2' = \left[\frac{-1 \pm \sqrt{1 + \frac{2(\gamma_2 - 1)(\dot{m}_A + \dot{m}_f) R T_{T2}}{P_2'^2 A_2'^2 \gamma_2 g_c M_w}}}{\gamma_2 - 1} \right]^{\frac{1}{2}}$$

(q) Calculate the total pressure after the dump at Station 3, by using the following equation:

$$P_{T3} = P_2' \left[(1 + \frac{\gamma_2 - 1}{2} M_2'^2)^{\frac{\gamma_2}{\gamma_2 - 1}} - 1 \right] e^{(-\frac{1}{2} N_D \gamma_2 M_2'^2)}$$

where N_D is obtained from Reference 5.

(r) Calculate the Mach number after the dump at Station 3.

$$X_3 = \frac{(\dot{m}_A + \dot{m}_f)}{P_{T_3} \, A_3} \sqrt{\frac{R \quad T_{T2}}{g_c \quad M_{w2}}}$$

$$M_3 = f \,(X_3)$$

(s) Calculate the static pressure at Station 3.

$$P_3 = P_{T3} \left(1 + \frac{\gamma_2 - 1}{2} M_3^2 \right)^{\frac{\gamma_2}{1 - \gamma_2}}$$

(t) Calculate the Mach number at Station 4 from the continuity and momentum equations.

$$Y_4 = Y_3 \sqrt{\frac{M_{w2}}{M_{w4}} \left[1 + \frac{\eta_c (T_{T4} - T_{T2})}{T_{T2}} \right]} \quad \frac{1 + \gamma M_3^2}{\left[1 + \gamma M_3^2 (1 - \gamma_2 \, C_{DB})\right]}$$

$$M_4 = f \,(Y_4)$$

(u) Calculate the total pressure at Station 4 from the momentum equation.

$$P_{T4} = P_{T3} \left[\frac{Z_3}{Z_4} - \frac{1}{2} \, C_{DB} \, \gamma_2 \, \frac{M_3^2}{Z_4} \, \frac{P_3}{P_{T_3}} \right]$$

(v) Calculate the Mach number at Station 5 from the continuity equation. It is assumed that the values of gamma, total temperature, and total pressure at Station 5 are the same as those at Station 4.

$$X_5 = X_4 \, \frac{A_4}{A_5}$$

$$M_5 = f \,(X_5)$$

(w) Calculate the static pressure at Station 5.

$$P_5 = P_{T_4} \left(1 + \frac{\gamma_4 - 1}{2} M_5^2\right)^{\frac{\gamma_4}{1-\gamma_4}}$$

(x) Compare the static pressure at Station 5 with the ambient pressure P_0. If these pressures do not compare reasonably well, adjust A_0 and return to Step (b).

(y) If the static pressure and P_0 match,

Thrust = $P_{T_4} A_5 Z_5 - P_{T_0} A_0 Z_0 - P_0 (A_5 - A_0)$

Isp = thrust/$\dot{m}_f$

Note: If the Mach number at any station exceeds one, reduce A_0 and return to Step (b). If the Mach number at Station 5 equals one and $P_5 \geq P_0$, this is a solution.

SECTION IV

STUDY RESULTS

1. IDEAL PROPANE EJECTOR RAMJET

Figure 3 presents the parametric performance data for a propane
fueled subsonic ejector ramjet at an altitude of 23,000 feet, A_5/A_3 = 0.55,
and 100% efficiencies. Plotted is the thrust coefficients (C_F) based on
free stream dynamic pressure and combustor area versus fuel specific
impulse (ISP). The dashed lines represent constant values of fuel-to-
air ratio and the solid lines represent constant values of free stream
Mach number. Several factors are evident from this figure. First,
it is noted that for this ideal case, as the fuel-air ratio decreases
the fuel specific impulse continues to increase while the thrust decreases.
Obviously, the specific impulse must maximize at some f/a ratio and then
decrease as f/a ratio is lowered further. This will be evident when
component efficiencies are introduced into the cycle. The second
prominent feature occurs above the stoichiometric fuel/air ratio (f/a
0.064). As more fuel is added above the stoichiometric point the
thrust continues to increase. This phenomenon is not present in the
conventional ramjet because the contribution of fuel momentum is not
considered in the ramjet cycle. In the ejector ramjet cycle as the fuel
flow rate continues to increase the fuel momentum increases and thrust
benefits accrue, at a loss in specific impulse. Also, it is noted
that specific impulse improves significantly with Mach Number over the
range considered.
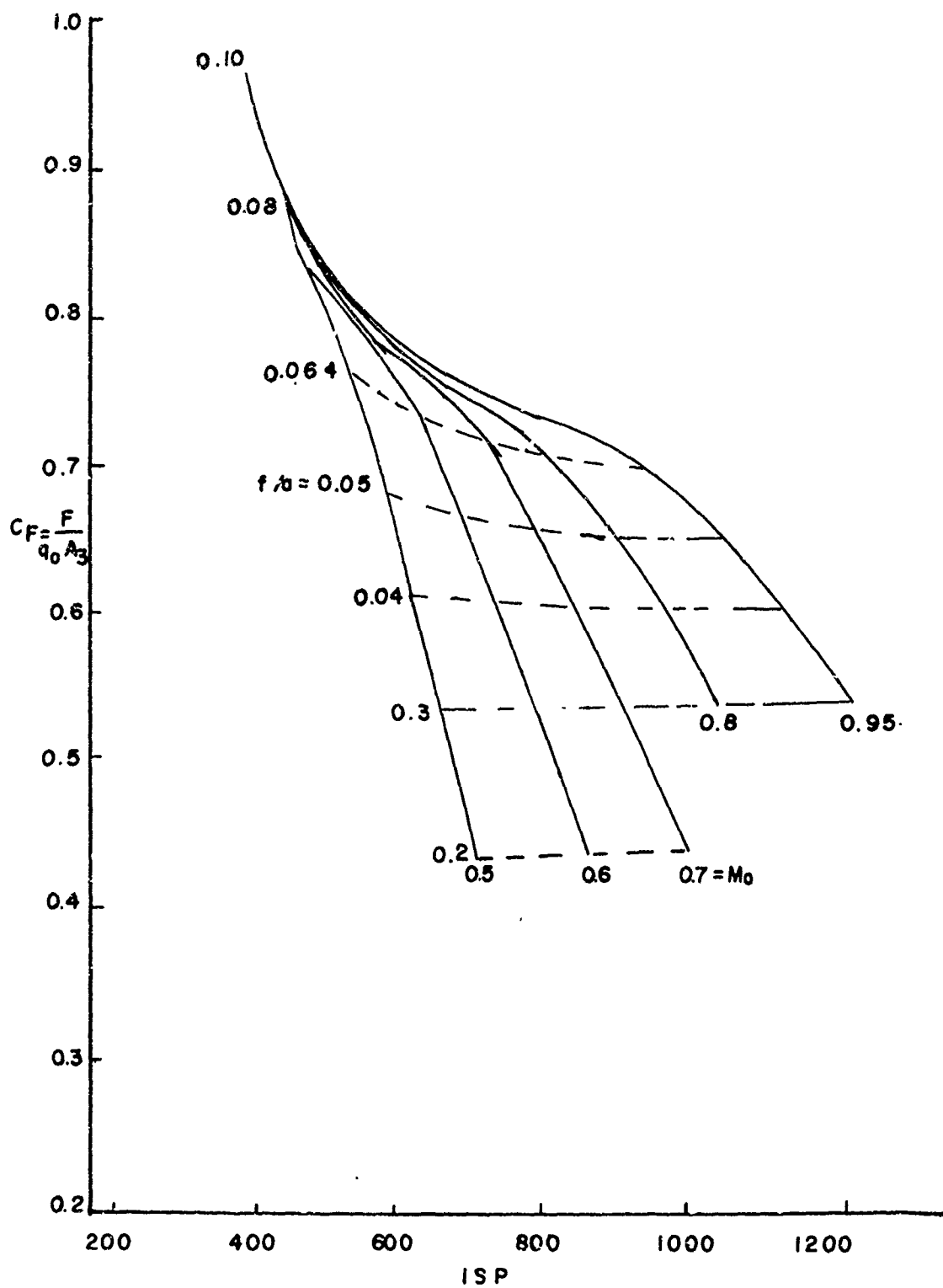
Figure 3. Ideal Ejector Ramjet Performance

2. PROPANE EJECTOR RAMJET ($C_{DB} = 4.0$, $\eta_c = 0.90$)

Figure 4 repeats the results of Figure 3 for a propane ejector ramjet except that a burner drag coefficient of 4.0 and a combustion efficiency of 0.90 has been included. If the figures are compared, it can be seen that the performance, both thrust coefficient and specific impulse, have been lowered by including the efficiencies. Also as the fuel-air ratio is decreased the specific impulse does not continue to increase as it did in the ideal case, but maximizes between $f/a = 0.02$ and 0.03 and decreases as f/a approaches zero. Figure 5 considers additive drag for an engine with $A_c/A_3 = 0.2047$. The design point at which this A_c/A_3 was chosen is $M_0 = 0.95$ and $C_F = 0.5$. Figure 6 is a composite of several constant Mach number lines taken from Figures 4 and 5. The dashed lines in Figure 6 stop a. the line representing full inlet capture. The additive drag effects on engine performance are small in magnitude but increase with increasing Mach number.

3. PROPANE EJECTOR RAMJET (DIFFUSER AND DUMP LOSSES)

It was pointed out previously that the ejector ramjet had a sudden dump into the combustor, which served as a flameholding device; therefore, perhaps the burner drag coefficient of 4.0 used previously was not appropriate. So in an attempt to use component efficiencies consistent with the ejector ramjet geometry, experimental data was obtained to account for the dump loss into the combustor and other data applied to the diffuser directly ahead of the dump. The method of accounting for these effects is described in Section III. A diffuser loss factor $\bar{C}_p$ of 0.51 and a dump loss factor N_D of 0.25 were used instead of a burner drag coefficient. A combustion efficiency of 90%

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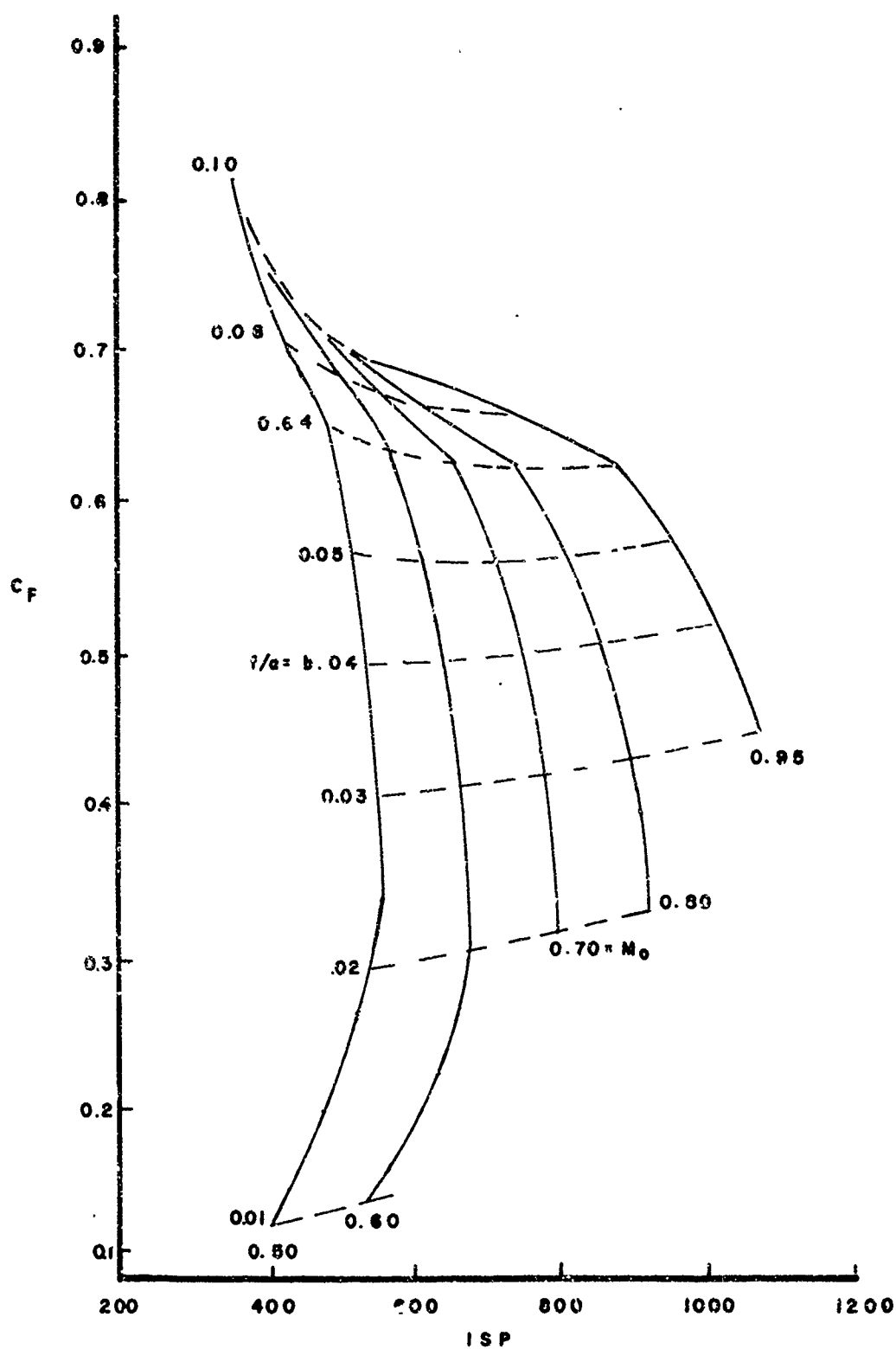
Figure 4. Ejector Ramjet Performance for $C_{D_B} = 4$ and $\eta_C = 90\%$
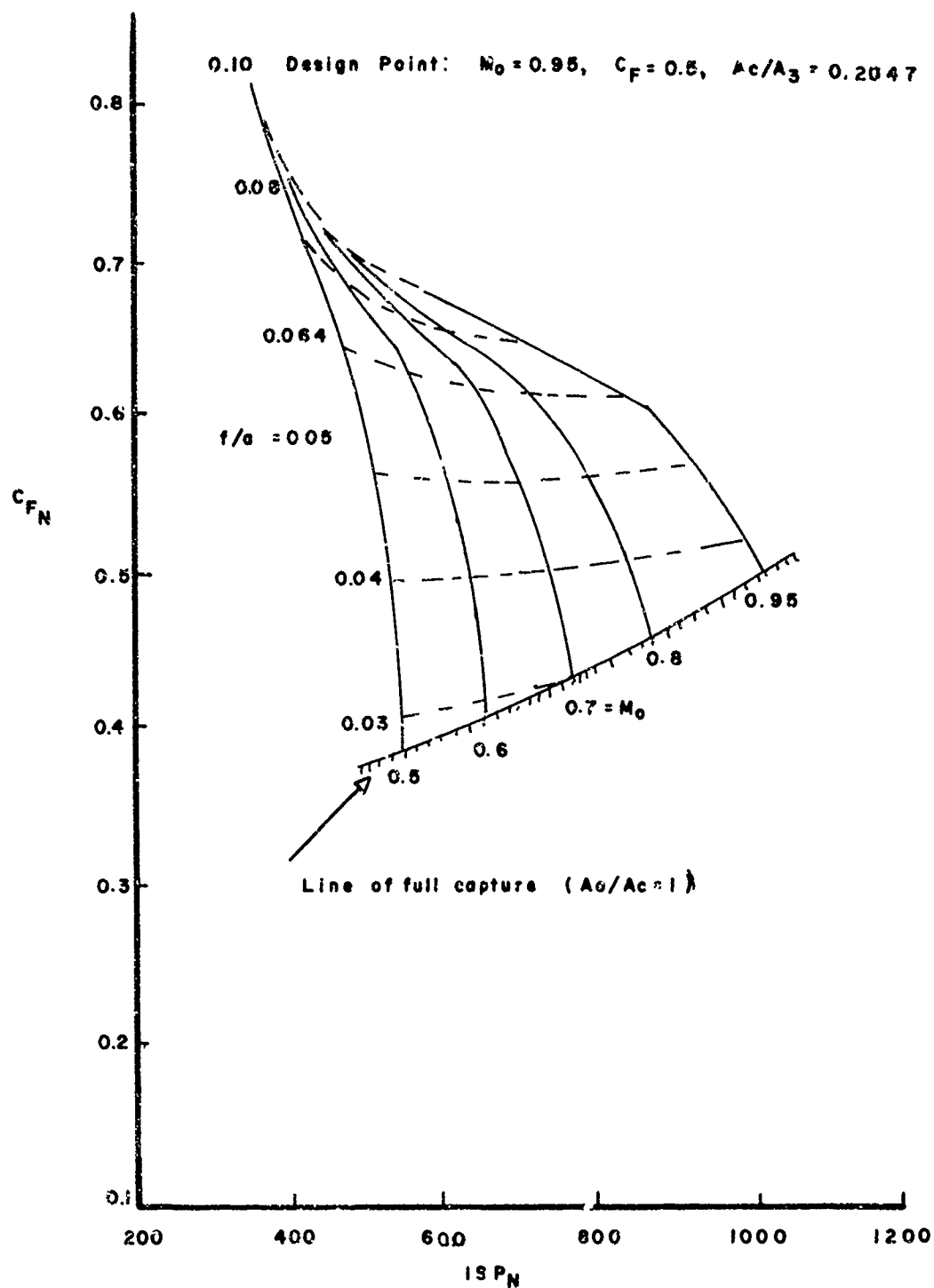
Figure 5   Ejector Ramjet Performance With Additive Drag, C_{D_B} = 4 and η_c = 90%
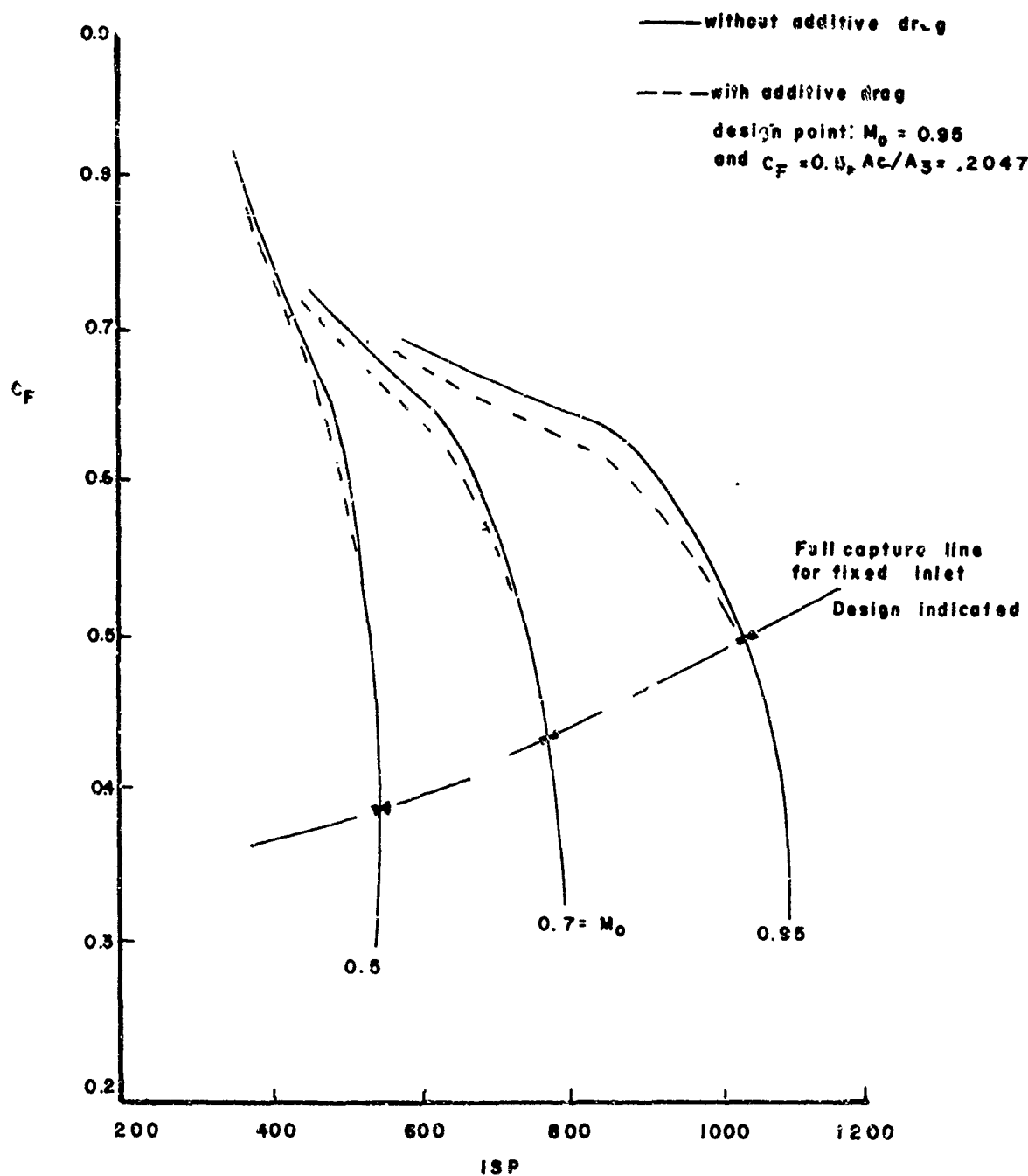
Figure 6. Effects of Additive Drag on Ejector Ramjet Performance With $C_{D_B} = 4$ and $\eta_c = 90\%$

was maintained. It can be seen from Figure 7 that this case with dump
and diffuser loss is worse than the previous case with combustion
efficiency of 90% and a burner drag coefficient of 4.0. The absolute
values of $\bar{C}_p$ and N_D are for the specific geometry evaluated and apply
only to that particular case.

Figures 8 and 9 show the effects of additive drag with an $A_c/A_3 = 0.1825$
which was chosen at the design point corresponding to $M_0 = 0.95$ and
$C_F = 0.5$. As was noted for the previous case with $C_{DB} = 4$, the additive
drag effects for this case are small.

4. IDEAL PROPANE RAMJET

Figure 10 presents the results for a propane-fueled ramjet with no
internal flow losses and an exit area ratio A_5/A_3 of 0.55 at 23,000 feet
altitude. Figure 10 is a plot of the thrust coefficient versus fuel
specific impulse. The same trends are present as for the ejector ramjet
(Figure 3) except that above the stoichiometric fuel-air ratio there
is no additional increase in the thrust coefficient since fuel momentum
is not considered in the ramjet cycle. Thrust coefficient increases
with f/a ratio as specific impulse decreases. Here, also, there is no
maximization of the specific impulse as the f/a ratio decreases. Again,
the specific impulse increases as the subsonic flight speed increases.
In general, the ideal ejector ramjet has better performance at fuel/
air ratios above approximately 0.025; however, this comparison assumes
no internal flow losses for either engine.
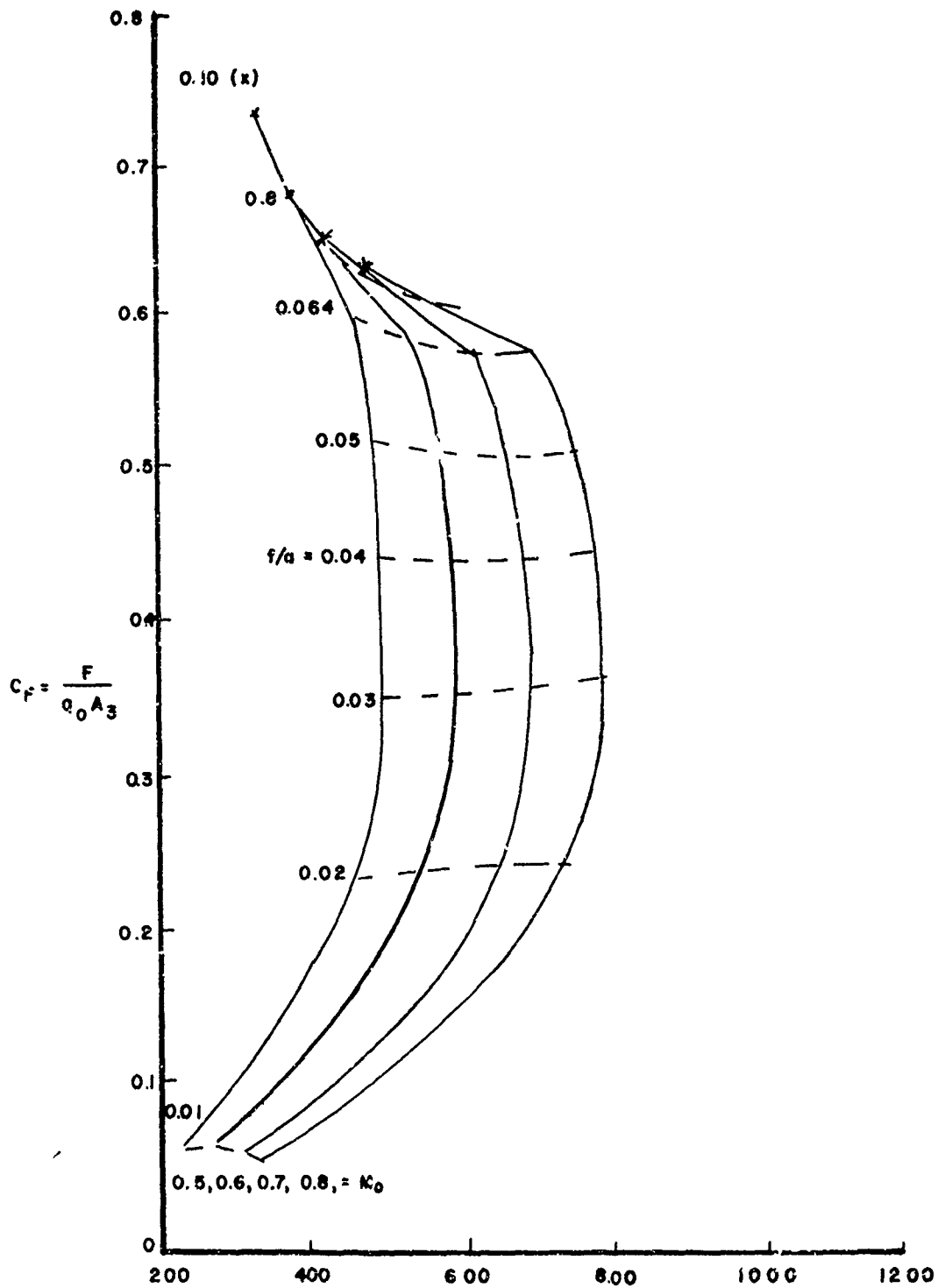
Figure 7. Ejector Ramjet Performance With Diffuser and Dump Losses
and $\eta_C = 90\%$
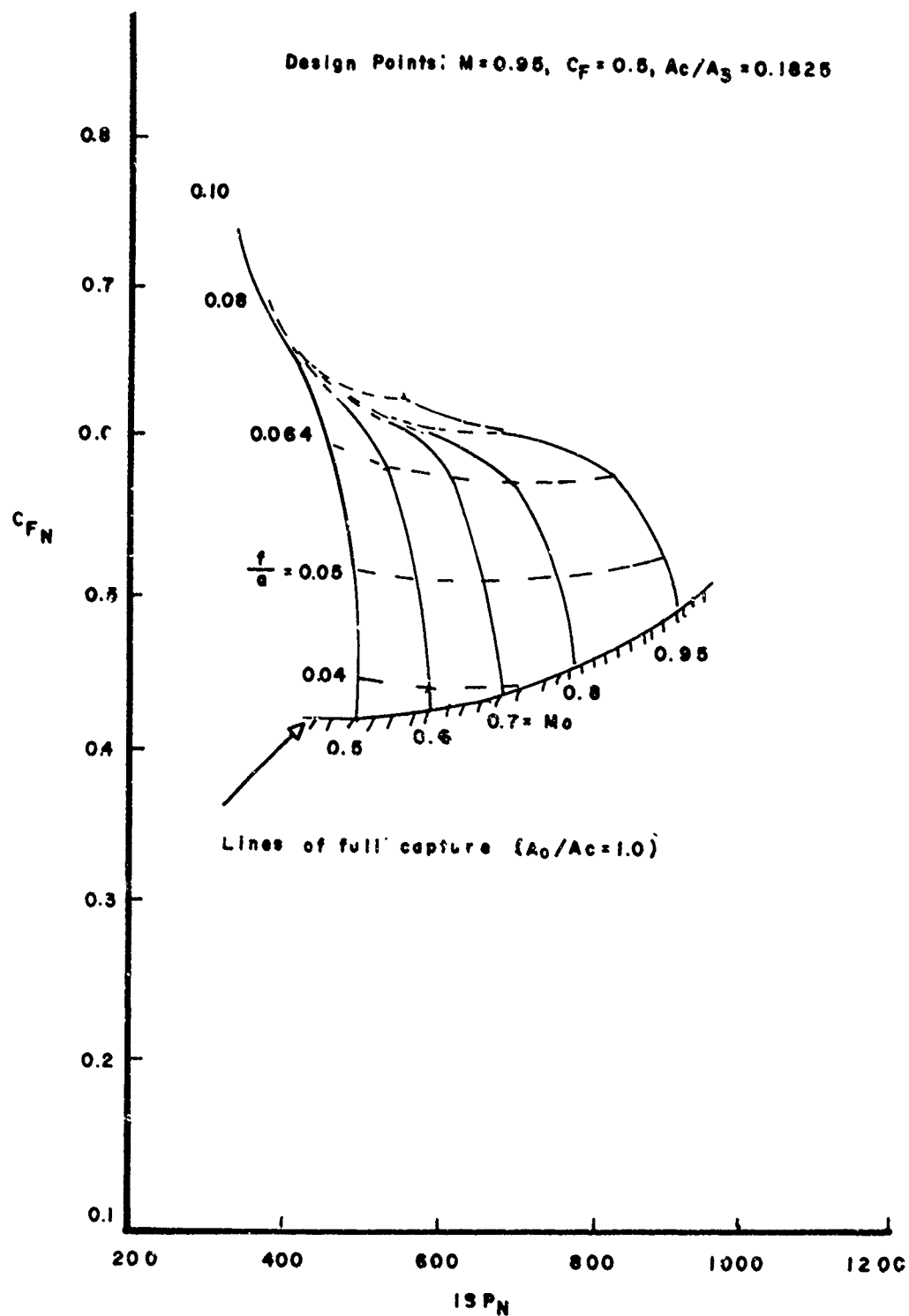
Figure 8. Ejector Ramjet Performance With Additive Drag, Diffuser and Dump Losses, and $\eta_c = 90\%$
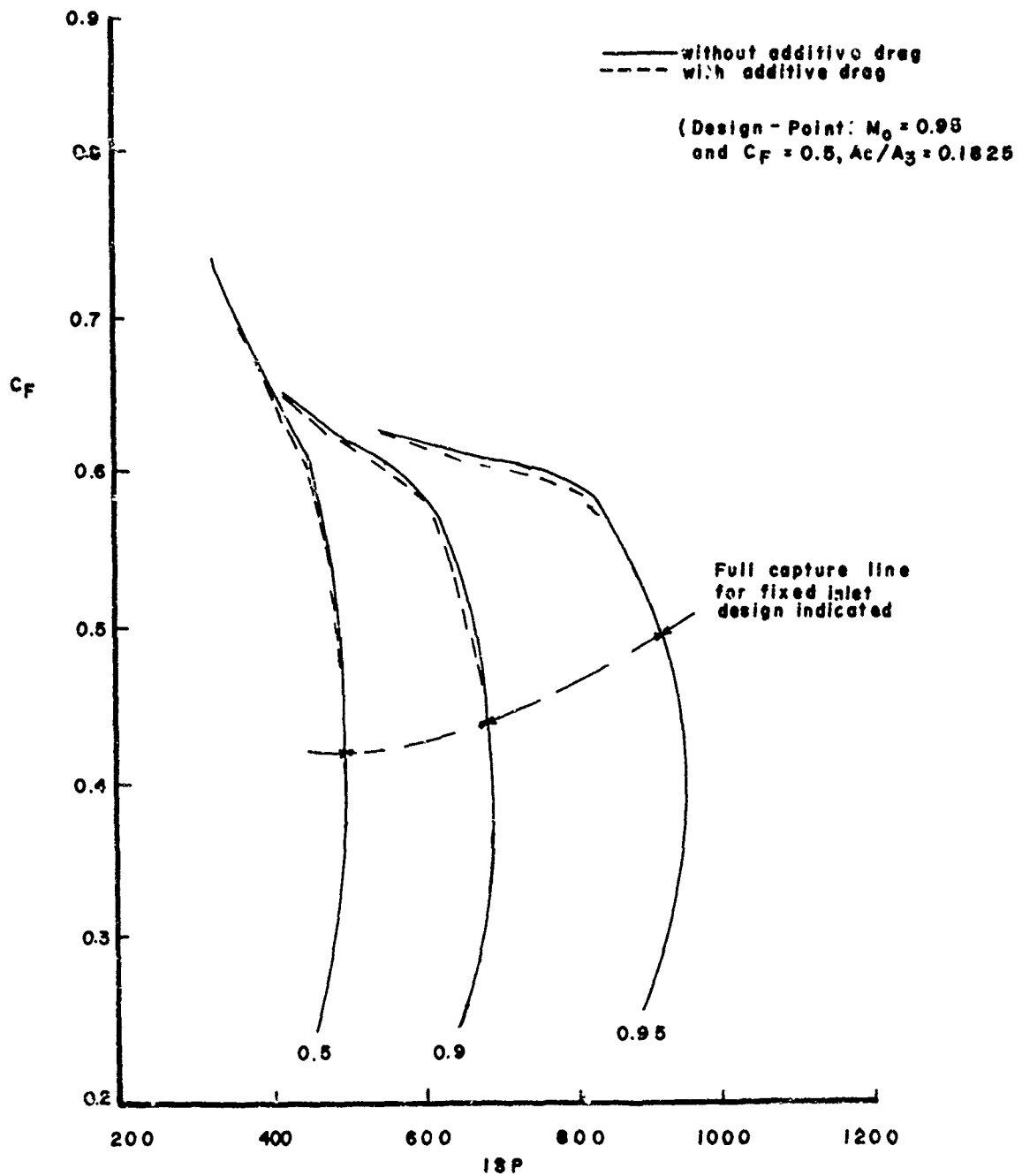
Figure 9. Effects of Additive Drag on Ejector Ramjet Performance With
Diffuser and Dump Losses, and η_c = 90%
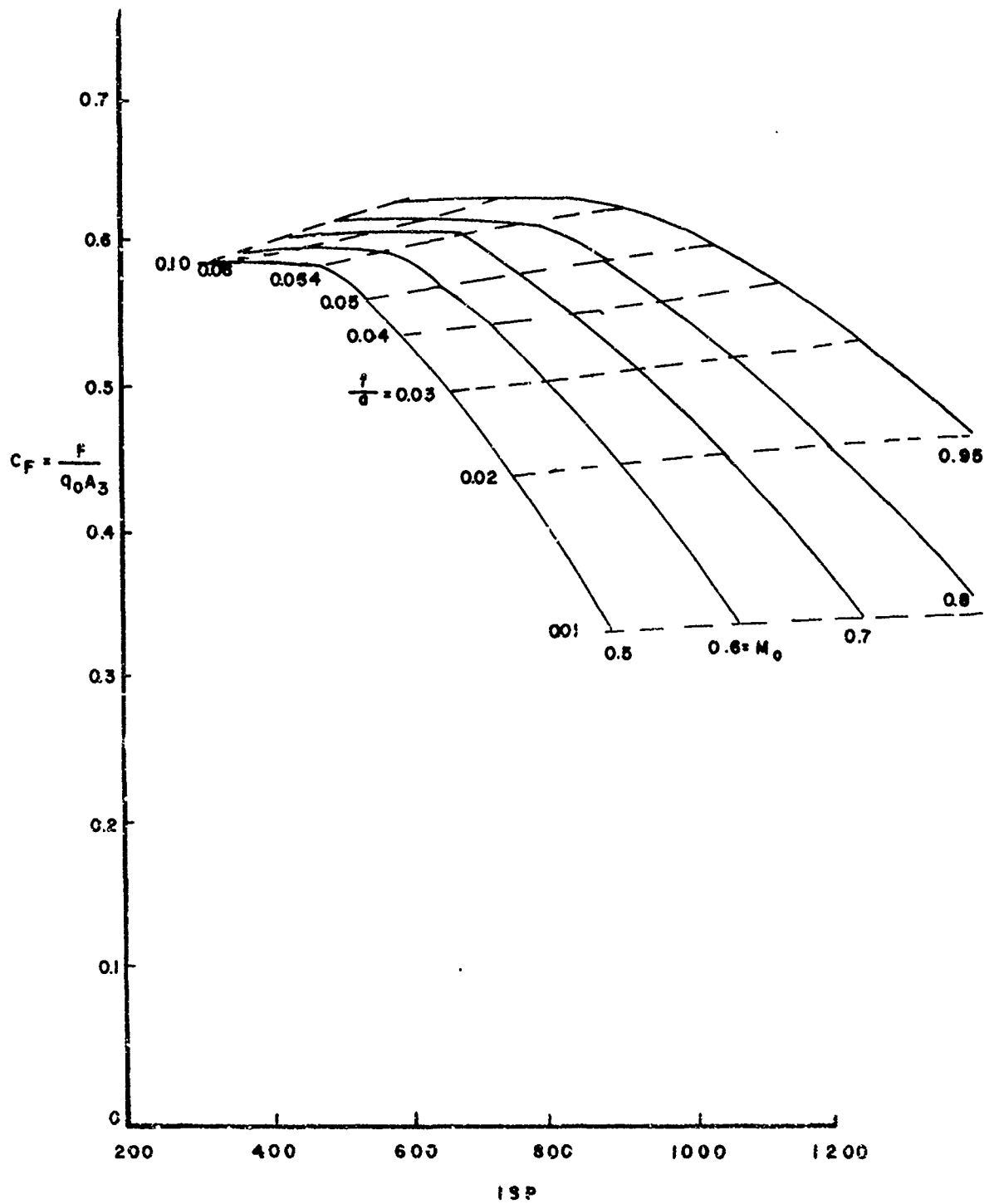
Figure 10. Ideal Propane-Fueled Ramjet Performance

5. PROPANE RAMJET (C_{DB} = 4.0 and η_c = 0.90)

Figure 11 presents the results when using a burner drag coefficient of 4.0 and a combustion efficiency of 0.90 for the propane ramjet. They are directly comparable to the ideal case, Figure 10. While the values of thrust and specific impulse are lower for the case with the burner drag and combustion efficiency, the basic trends are the same with the exception of the lower fuel-air ratios. As the fuel-air ratio decreases, the specific impulse does not continue to increase; it maximizes and then decreases as the f/a ratio approaches zero.

6. IDEAL JP-4 RAMJET

Figure 12 presents the ideal performance for a JP-4 fueled engine. This data is similar to the data shown in Figures 10 and 11 for the propane ramjet. Again no internal losses are assumed and A_5/A_3 is 0.55 at an altitude of 23,000 feet. The same trends are evident although the propane ramjet has a slight advantage at the low and medium fuel-air ratios. Above the stoichiometric fuel-air ratio (0.068 for JP-4 and 0.064 for propane) the performance is almost identical.

7. JP-4 RAMJET (C_{DB} = 4.0 and η_c = 0.90)

Figure 13 presents the results for a JP-4 ramjet with a burner drag coefficient of 4.0 and a combustion efficiency of 0.90. Figure 13 is directly comparable to Figure 12.

Figures 14 and 15 show the effects of additive drag with A_c/A_3 = 0.1976, which was chosen for the design case of M_o = 0.95 and C_F = 0.5.
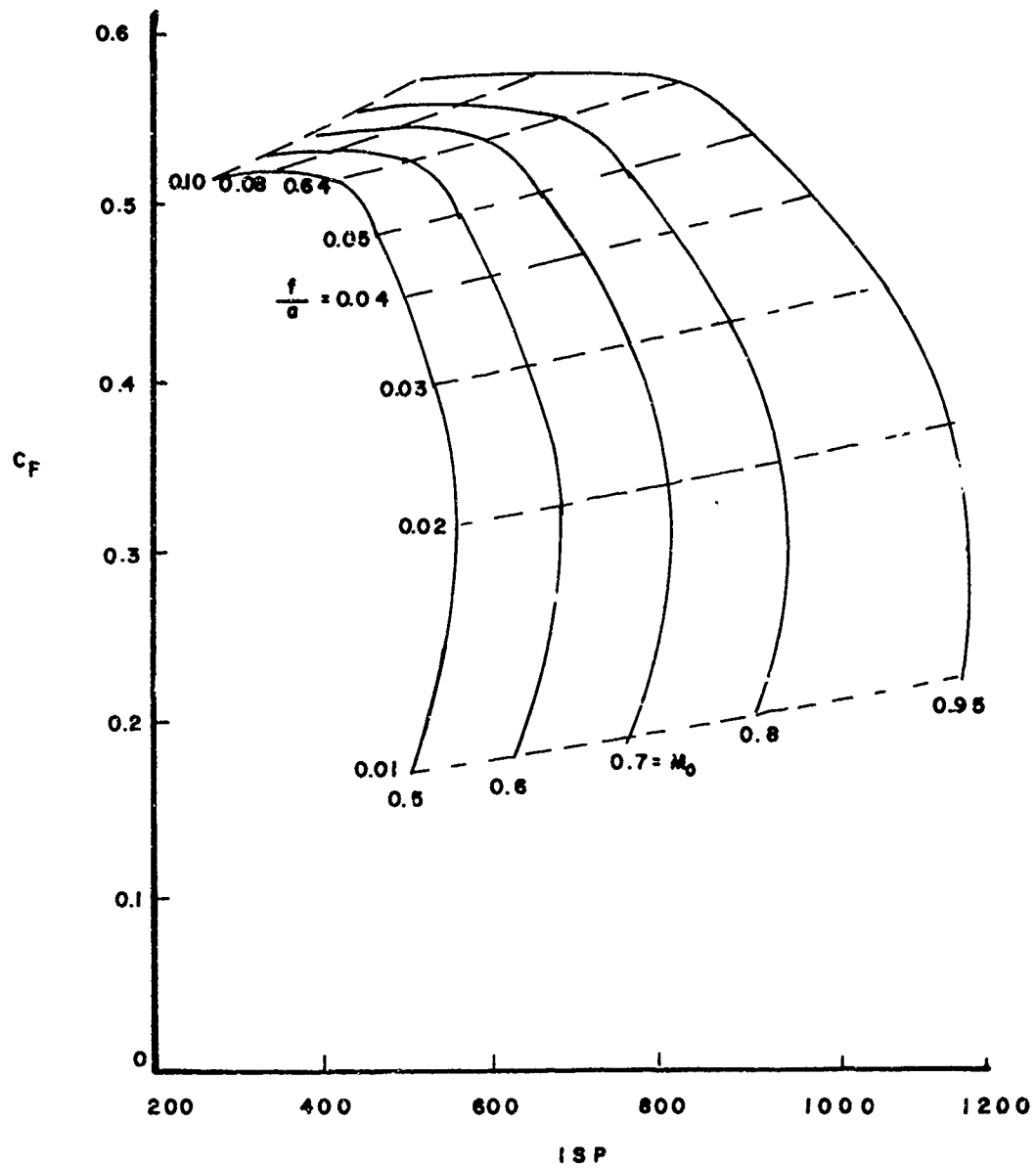
Figure 11. Propane-Fueled Ramjet Performance With C_{DB} = 4 and η_c = 90%
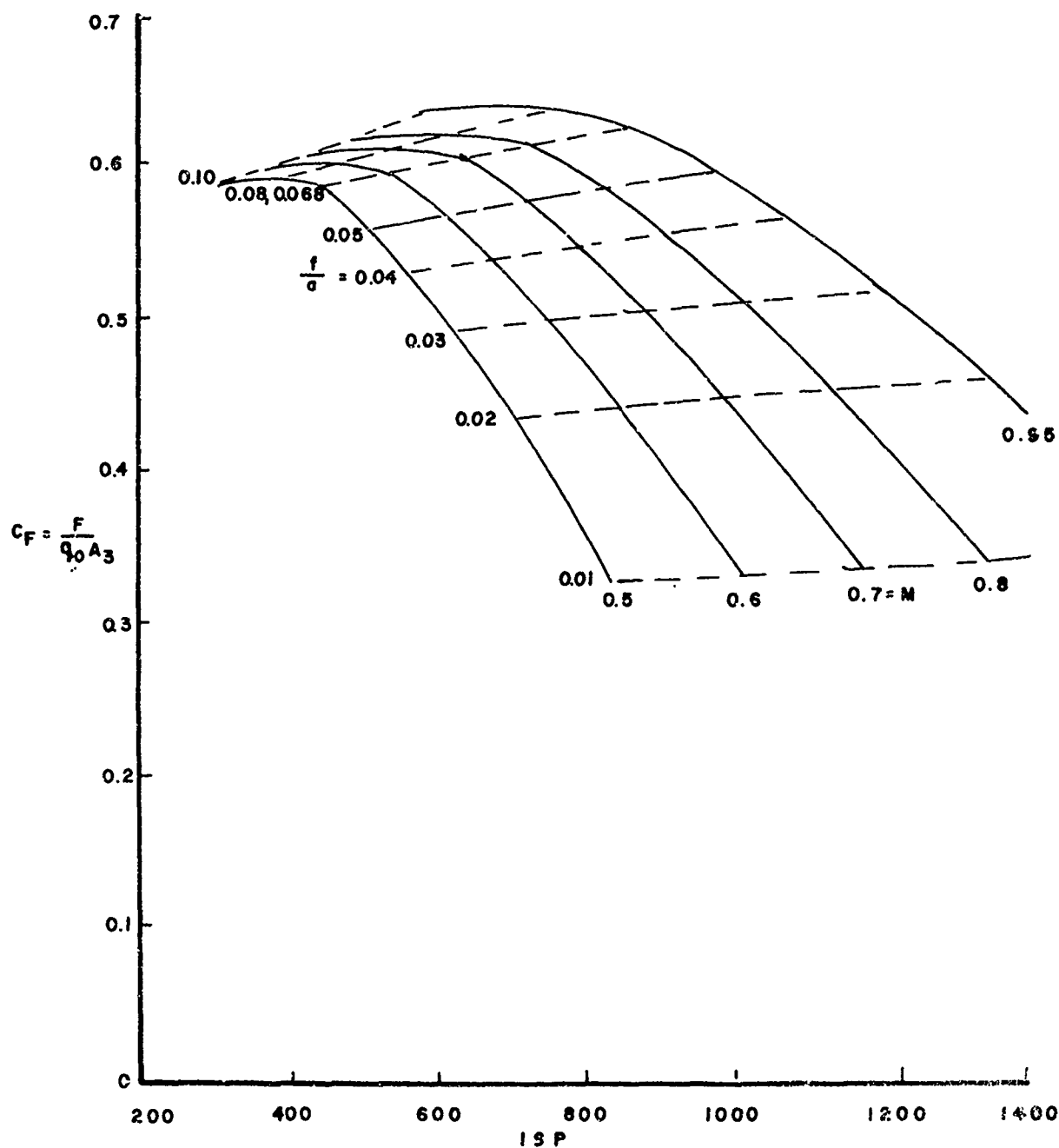
Figure 12.   Ideal JP-4 Fueled Ramjet Performance
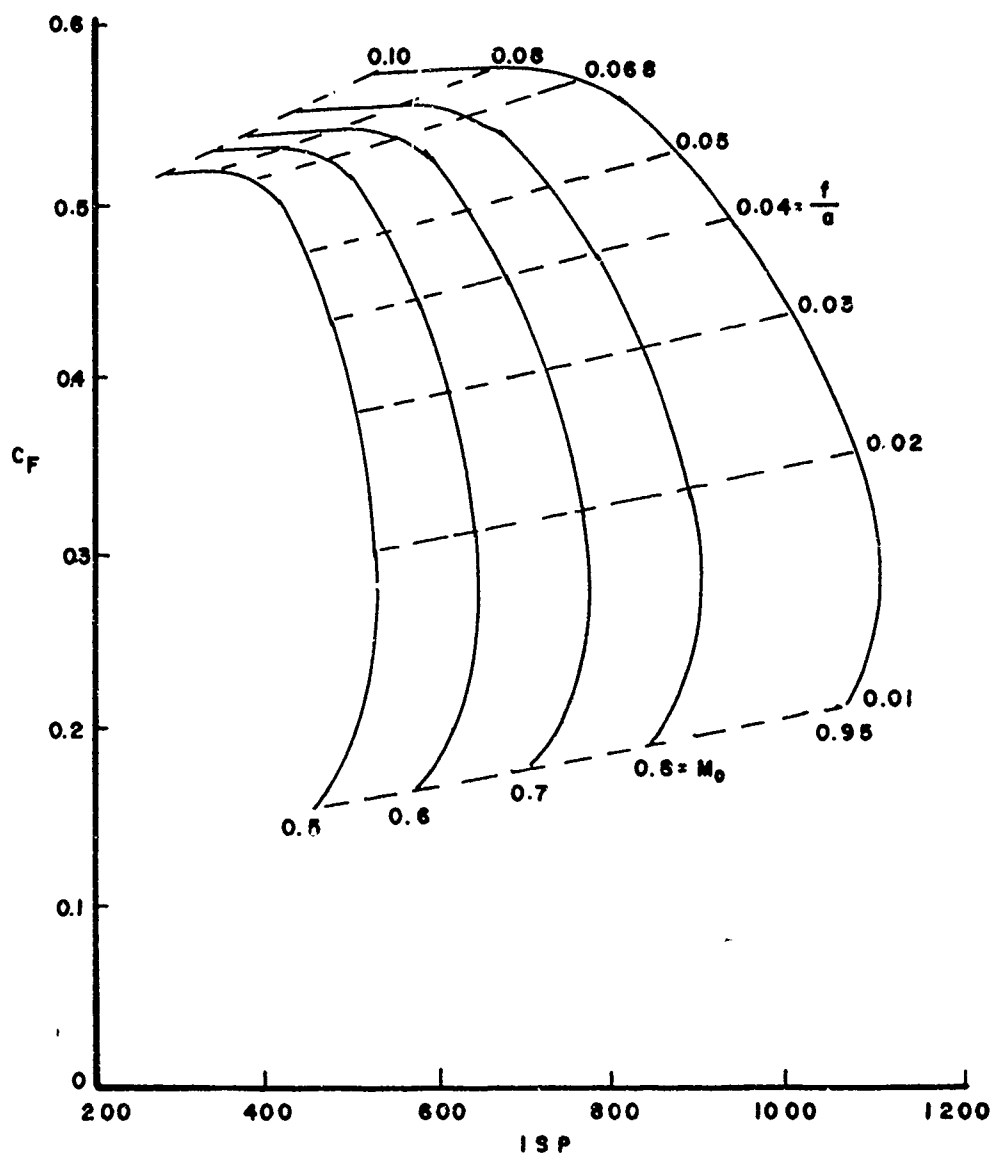
Figure 13. JP-4 Fueled Ramjet Performance With C_{D_B} = 4 and η_c = 90%

Design Point: $M_0 = 0.95$, $C_F = 0.5$, $Ac/A_3 = 0.1976$
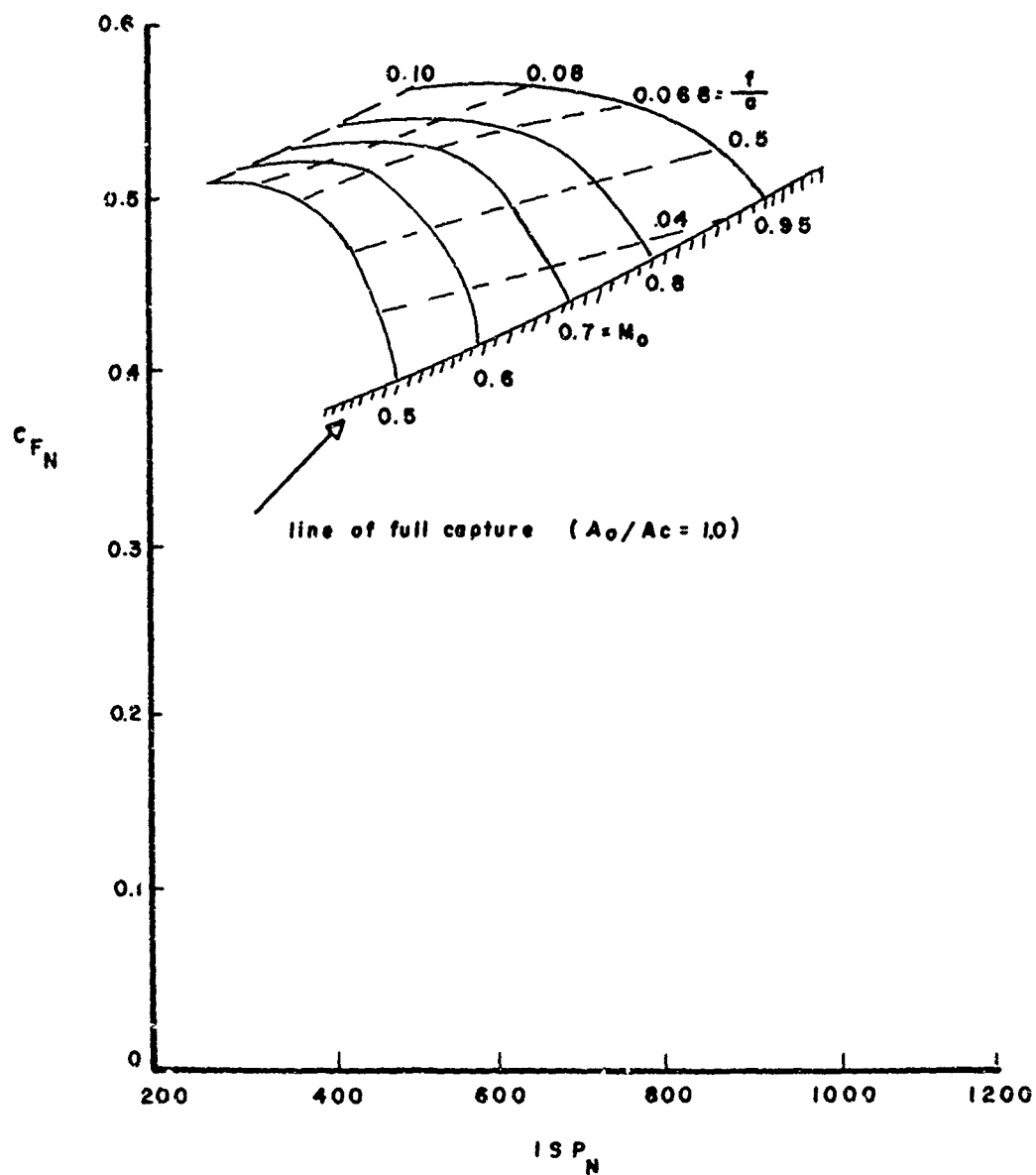
Figure 14. JP-4 Fueled Ramjet Performance With Additive Drag, $C_{D_B} = 4$, and $\eta_c = 90\%$
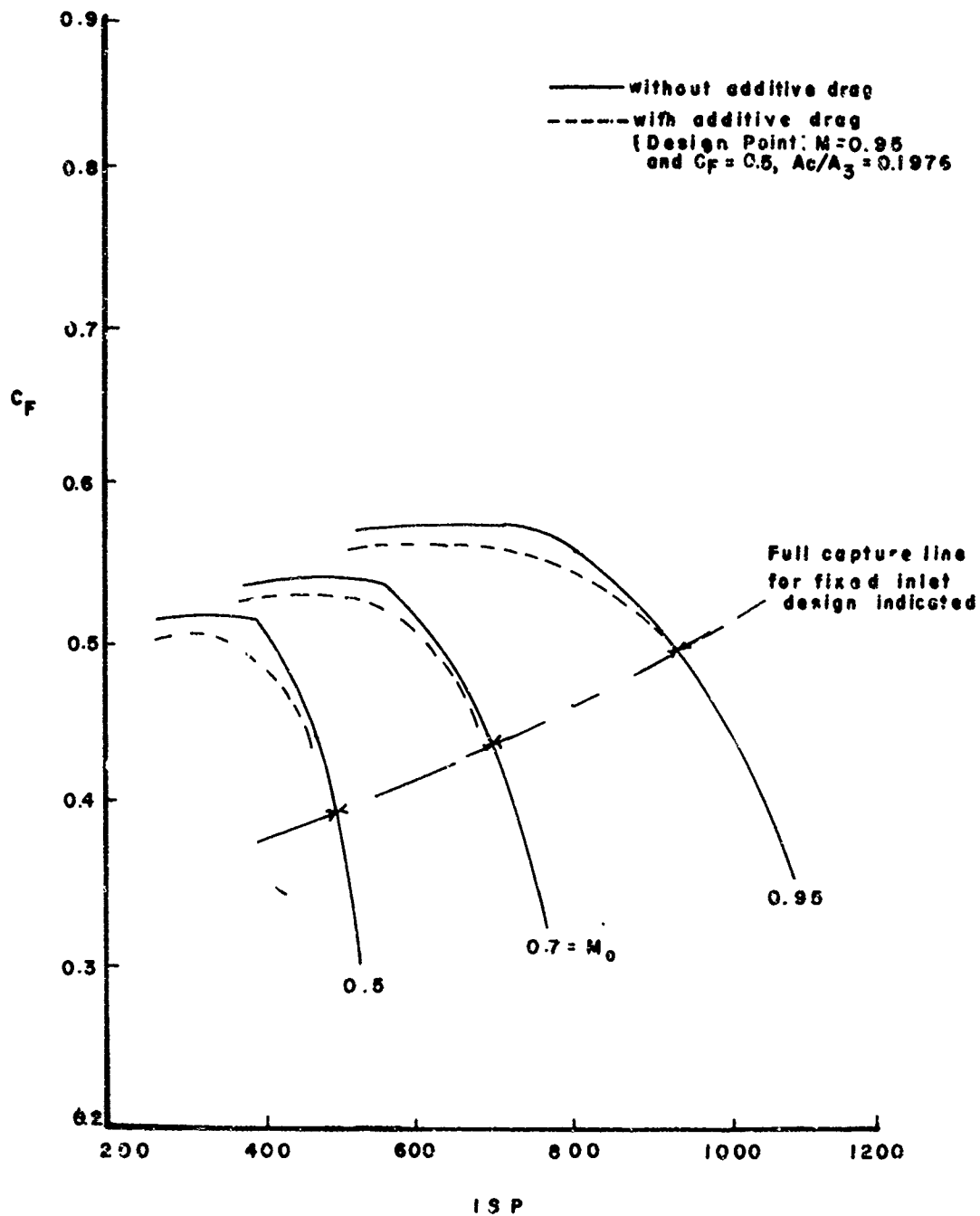
Figure 15. Effects of Additive Drag on JP-4 Fueled Ramjet Performance
With C_{D_B} = 4 and η_c = 90%

SECTION V

COMPARISONS

The ramjet and ejector ramjet performance parametrics shown herein
can be used for several comparison purposes only. The results are valid
for the assumptions made. In general, an application requires that an
engine operate over a wide envelope with fixed geometry, which necessitates
considering additive drag. In addition, the external drag of the engine
nacelle must be included, as well as any vehicle/engine interference
drag. Without these specific effects, the following general comparisons
can be reached.

Figure 16 compares the parametric performance of the ideal engines
at Mach 0.7. The lowest point on each line is for $f/a = 0.02$ and the
highest point is for $f/a = 0.1$. As the fuel/air ratio increases, the
thrust increases at a sacrifice in specific impulse. At the very low
fuel/air ratios the performance is nearly identical. As the fuel/air
ratio increases, the advantages of the ejector ramjet become apparent.
The "X" mark on each line indicates a stoichiometric fuel/air ratio.
Thrust levels below this mark indicate lean engine operation, and those
above this mark indicate fuel rich operation.

The propane ramjet and the propane ejector ramjet can be compared
in many ways. As noticed on the ramjet curves, the thrust maximizes
at about the stoichiometric fuel/air ratios; richer mixtures are of no
advantage to the ramjet. Comparing the ideal engines at this stoichiometric
fuel/air ratio indicates that the ideal ejector ramjet has a thrust
advantage of 18% and a specific impulse advantage of 11%. The ejector
ramjet can increase thrust at a sacrifice in impulse by operating fuel
rich; this is no advantage to the ramjet.

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Let us compare the ejector ramjet operating at a f/a = 0.1 and the ramjet operating at stoichiometric. For this case, the ejector ramjet has a thrust advantage of 37% but a specific impulse that is only 76% of that possible with the ramjet. Figure 17 shows the same comparisons at Mach 0.95. The same comparisons can be made from Figure 18 for C_{DB} = 4 and η_C = 90%. With both engines operating stoichiometrically, the ejector ramjet has a 17% thrust advantage and a 10% specific impulse advantage, slightly lower than for the ideal case. With the ejector ramjet operating at f/a = 0.1 and the ramjet at stoichiometric, the ejector ramjet has a 35% thrust advantage but again at 76% of the ramjets' specific impulse.

If the ejector ramjet has the drag predicted from References 4, 5, and 6, and the ramjet has a C_{DB} = 4 and η_C = 0.9, we obtain the following results. With both engines operating stoichiometrically, the ejector ramjet has an 8% thrust advantage and a 5% specific impulse advantage over the ramjet. With the ejector ramjet operating at f/a = 0.1, its thrust advantage over the ramjet is 21% but its specific impulse is only 65% that of the ramjet. Similar comparisons can be made at Mach 0.95 and 23,000 feet from Figure 19; it must be pointed out, however, 'that this comparison is made at a maximum thrust level and at a very low specific impulse level, which gives the maximum potential advantage to the ejector ramjet. For a cruise application a lean fuel/air ratio would likely be chosen to maximize specific impulse; at a condition of say f/a = 0.3, the advantage of the ejector ramjet is considerably reduced or even eliminated. For instance, at f/a = 0.3, the ramjet would produce 16% more thrust at 10% higher specific impulse. One parameter which

is important to the effectiveness of the ejector ramjet is the ratio
of the primary to the inlet air stream thrust. As this parameter
increases, the ejector ramjet becomes more effective in its pumping action.
Figure 20 is a plot of this stream thrust ratio versus fuel/air ratio for
various flight mach numbers. As can be seen, this parameter increases
with increasing fuel/air ratio; therefore, the pumping action of the
ejector ramjet will be greater at the higher fuel/air ratios. This
effectively increases the amount of air flowing through the engine,
thus giving more thrust than is possible with the conventional ramjet
at the higher fuel/air ratios.
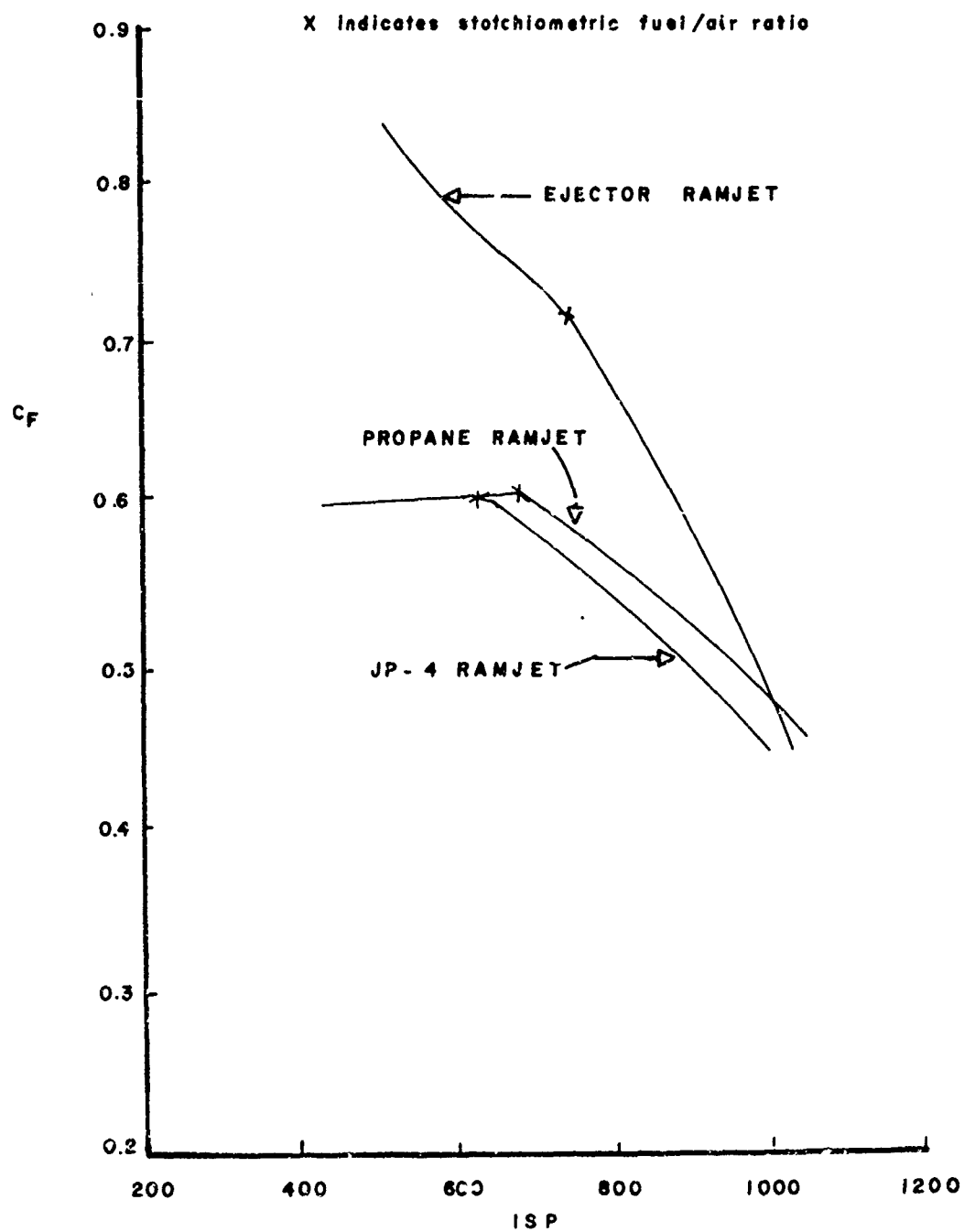
Figure 16. Comparison of the Ideal Engines at $M_0 = 0.7$

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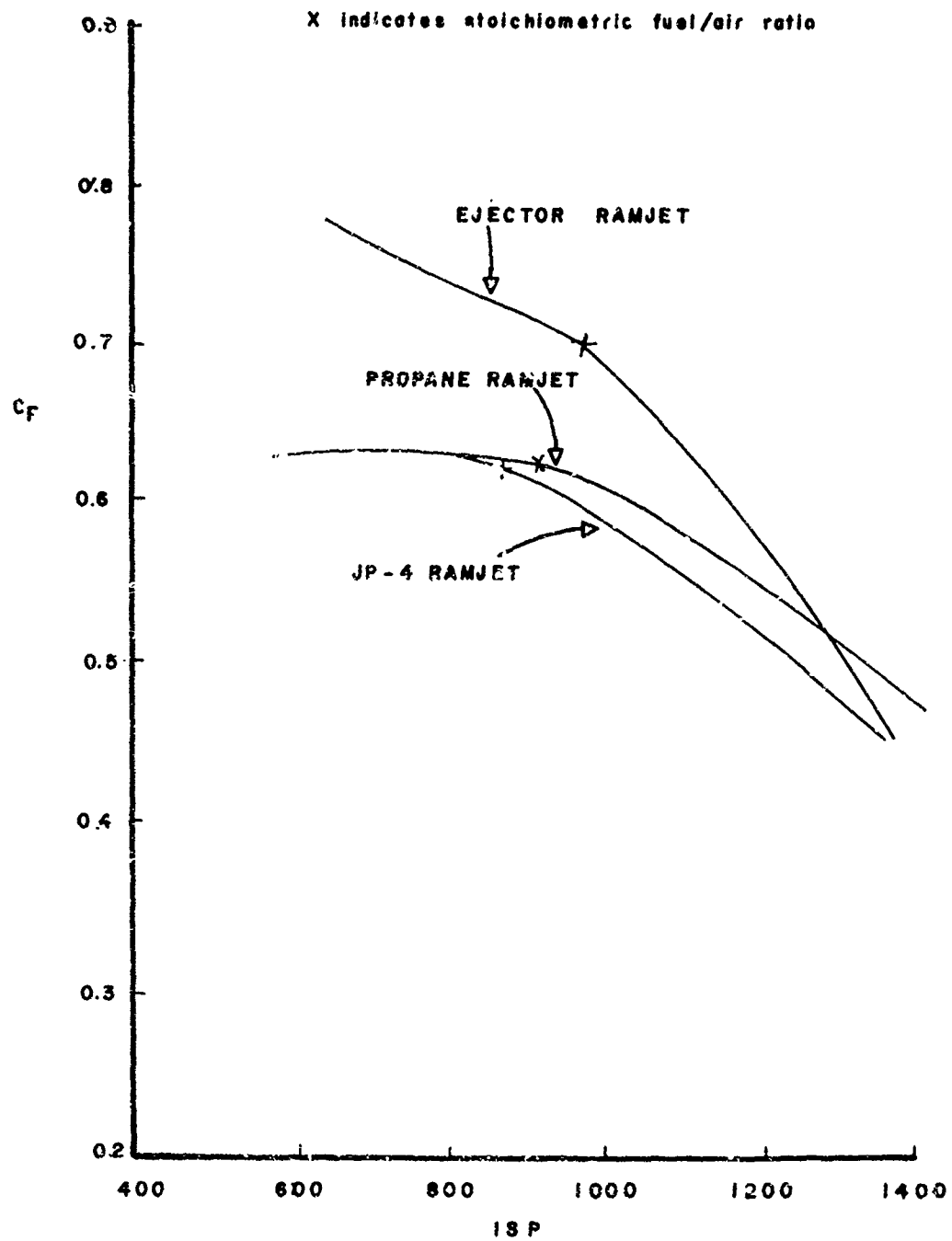
Figure 17. Comparison of the Ideal Engines at $M_0 = 0.95$
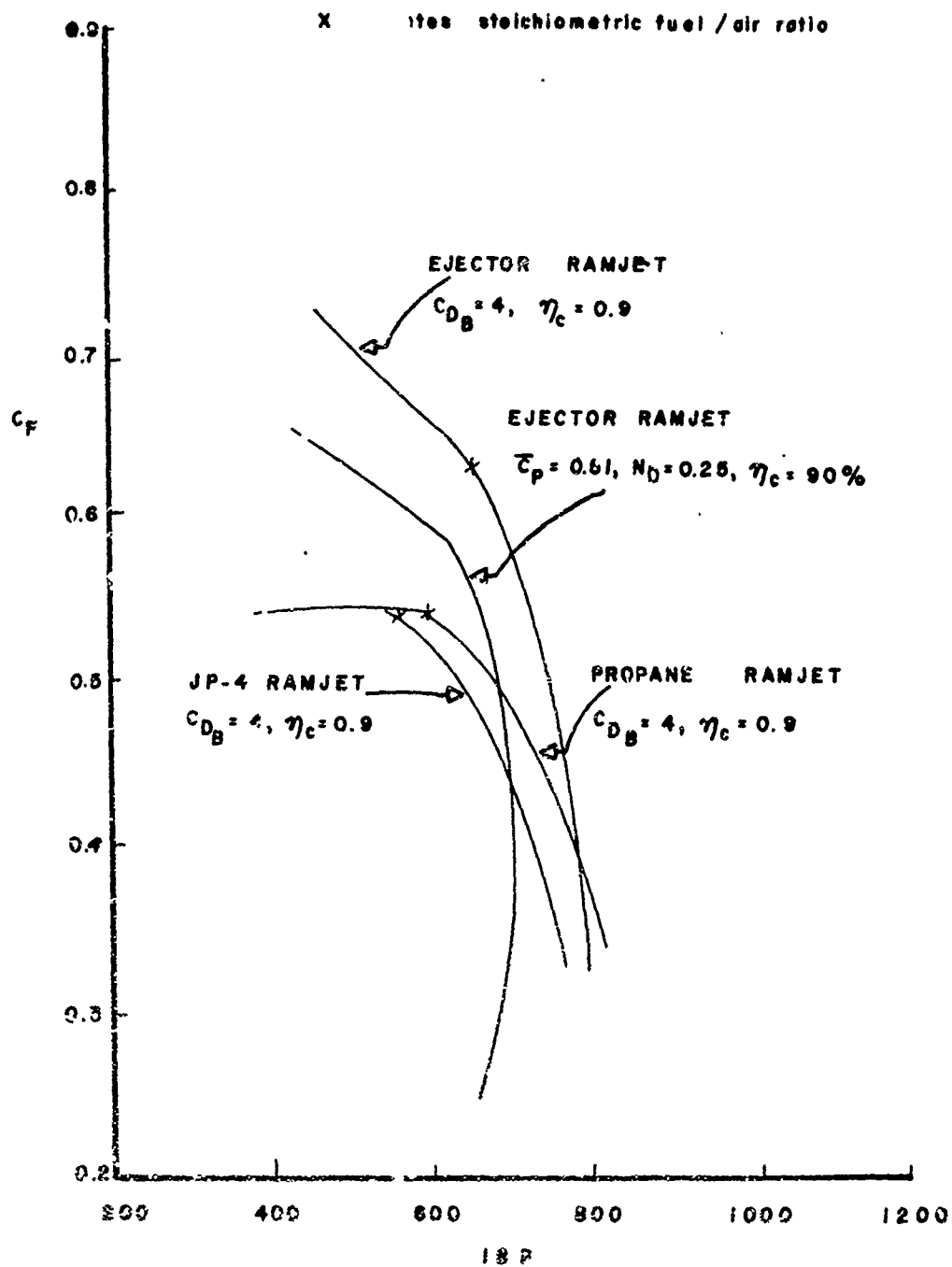
Figure 18. Comparison of the Engines With Efficiencies at $M_0 = 0.7$
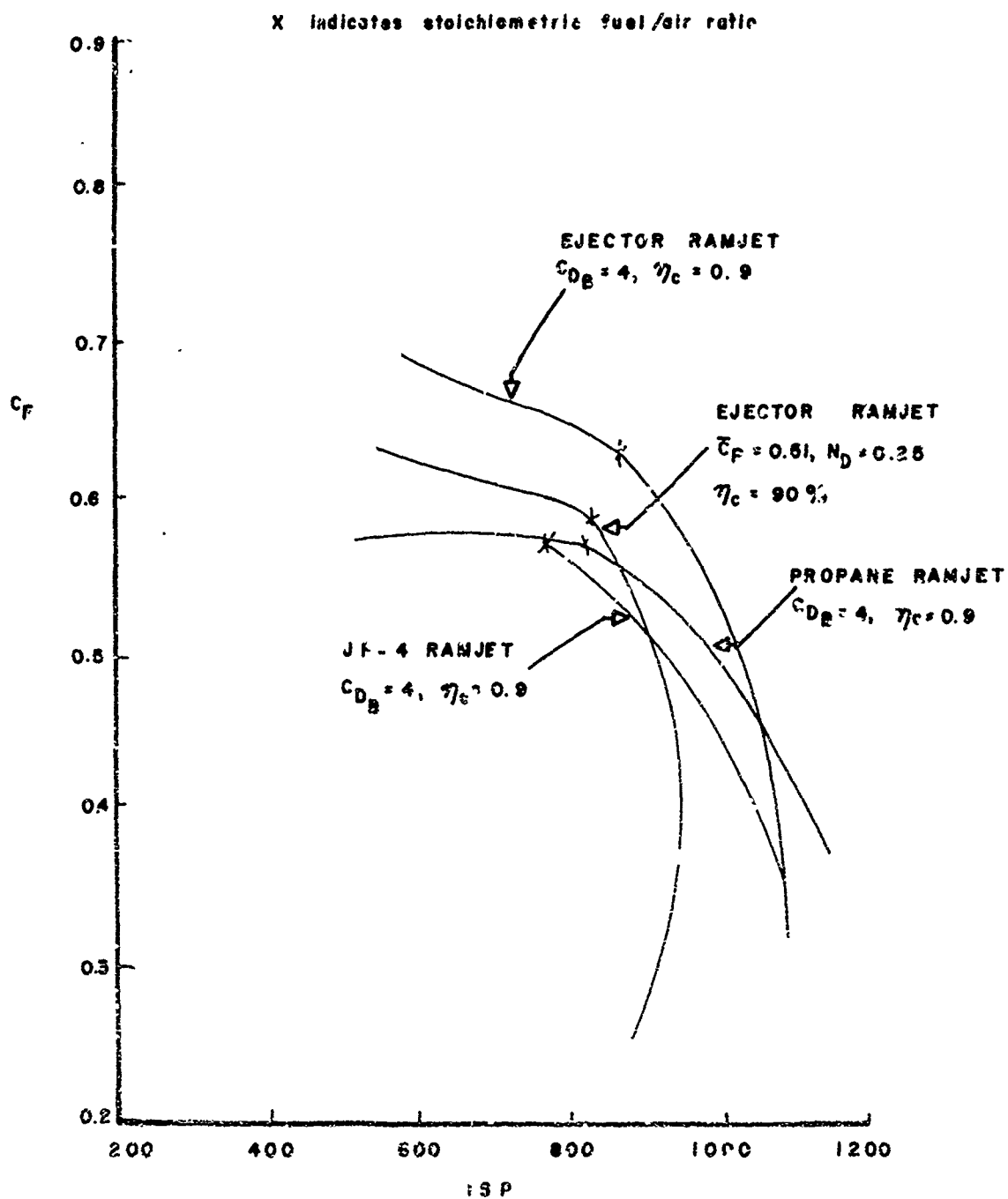
Figure 19. Comparison of the Engines With Efficiencies at M_0 = 0.95
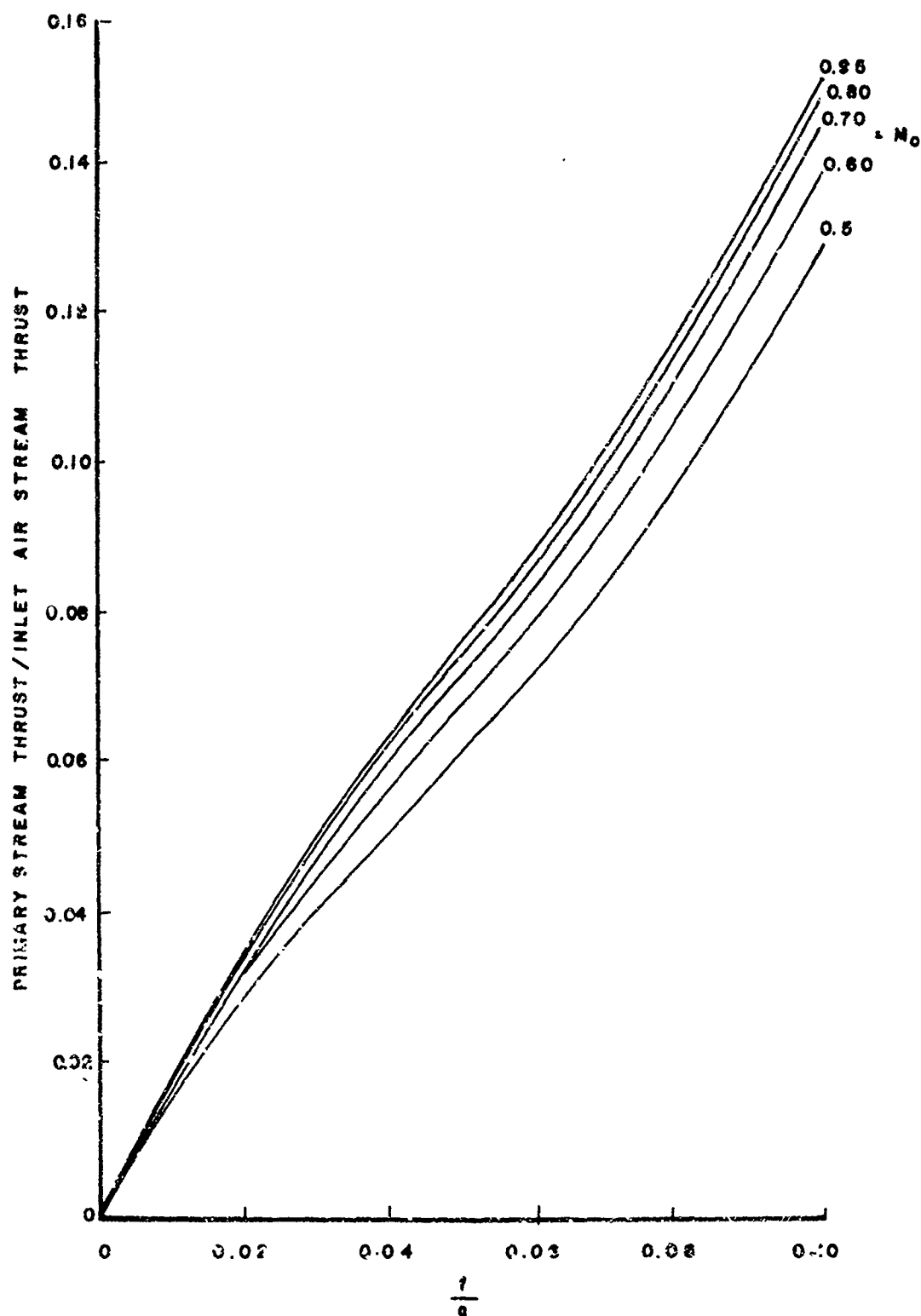
Figure 20. Ejector Ramjet Stream Thrust Ratio

SECTION VI

CONCLUSIONS

The potential performance of the ejector ramjet and the conventional ramjet have been determined. At high fuel/air ratios, the ejector ramjet has a thrust advantage over the conventional ramjet. The relative ranking of these two engine systems can change drastically, however, depending on the internal flow losses and combustion efficiency assumed in the analysis. In addition, the relative advantage changes greatly with the fuel/air ratio considered. The assumptions of $C_{DB} = 4.0$ and $\eta_c = 0.90$ for the ramjet are considered as state-of-the-art values for JP-fueled ramjets. The ejector ramjet losses assumed from References 3, 4, and 5 are considered representative, although data from a real engine of this type is lacking. Predictions of internal drag in References 3, 4, and 5 are based on experimental data. Comparing these cases shows that the ejector ramjet has an advantage at the high fuel/air ratios and the conventional ramjet has an advantage at the low fuel/air ratios. The reason for this difference is that with large fuel/air ratios the ejector pumping action is greater and the cycle pressure is increased, while at the lower fuel/air ratios the ejector pumping action is less. This is directly related to the momentum ratio of the ejector to the inlet air stream which increases as the fuel/air ratio increases.

The data contained in this section is parametric, with no fixed inlet size. A real engine with a known capture area will have an actual thrust lower than that estimated herein when additive drag and external

drag are included. This was illustrated in Section IV for one particular design point. This thrust decrement should affect each engine similarly, however, and should not change the relative ranking derived from this comparison.

APPENDIX I

ENGINE PERFORMANCE COMPUTER PROGRAM
INPUT AND OUTPUT PROCEDURES

For ease of operation, the data read into the program has been
divided into four sets: (1) the fuel data set, which contains the
tables of gamma, molecular weight, and temperature rise for the combustion
products as a function of initial temperature and fuel-air ratio; (2) the
engine geometry and the efficiency parameters, initial values of which
are built into the program; since this set of data is entered in Namelist
form, only those parameters having values different from the initial
values need be entered; (3) flight parameters at which the engine is
to operate, including the Mach numbers, altitudes, and fuel-air ratios
for which engine performance is to be calculated; (4) the job title
and the job code. The order of the first three data sets in the data
deck is not fixed, but the fourth set must appear last.

Each data set is identified by a key word which alerts the program
that the following data belongs to a particular data set. The key words
corresponding to the above four data sets are: FUEL, GEOMETRY, RANGE,
and PROBLEM. Each key word must start in column one. Tables I through
IV display the form of all the input data cards.

Table I shows the format for the fuel card set. Card 1 contains
the word, FUEL, starting in column one. Nothing else appears on this
card. Card 2 contains two numerical values: the number of fuel-air
ratios to be entered later in columns 1-10, and the number of initial

air total temperatures in columns 11-20. Card 3 gives the list of fuel-air ratios, starting in column 11, with six numbers per card; up to three cards may be required. The first ten and the last ten columns of these cards are reserved for identification data. (This identification data is not used by the computer.) The other lists of data in this set are entered on the same format. Each list begins on a new card.

Table II shows the variables that are entered on a Namelist card. A description of this type of data entry is given in the Fortran Extended manual.

Table III shows the format for the flight parameters. Card 1 contains the word, RANGE, starting in column one. The second card contains the number of Mach numbers, number of altitudes, and the number of fuel-air ratios. Ten spaces are allotted per number, starting in column one. The third card contains the list of Mach numbers, where each number is allotted ten spaces. The other two lists are similar, except that the fuel-air ratio list may require more than one card to complete the list. Figure 21 shows a typical data deck.

The printed output from the program gives the cycle performance and many engine parameters. Line 1 shows the problem title and the altitude. Line 2 shows the capture area in square feet, the conventional thrust in pounds, the corresponding thrust coefficient, specific impulse, specific fuel consumption, fuel-air ratio, and the flight Mach number. Line 4 shows the values of thrust in pounds, thrust coefficient, specific impulse, and specific fuel consumption, which have been corrected for

additive drag. Line 5 presents the engine stations and serves as a
title for the data immediately below. Column titled E presents data for
the exit of the ejector, which is used only for ejector ramjet problems.
Line 6 gives the Mach number at each station. Line 7 presents some of
the important values of gamma that were used. Line 8 shows the flow
area in square feet at each engine station. Line 9 shows the pressure
in atmospheres at each engine station. Line 10 shows the total pressure
in atmospheres at some of the engine stations. Line 11 gives the total
temperature in °R at some of the important engine stations. Line 12
shows the stream thrust in pounds force for some stations. Line 13
shows the molecular weight at two stations. Finally, the last line shows a
convergence parameter titled cycle, the free stream pressure in lbs/ft^2
the pressure at the engine exit in lbs/ft^2, the air flow rate in lbs/sec,
and the fuel flow rate in lbs/sec. A sample output is shown in Figure 22.

TABLE I - FUEL CARDS

Card Order	Contents	Format
1	FUEL	A10
2	Number of fuel-air ratios (max value - 18) Number of initial air temps (max value - 12)	2I10
3	List of fuel-air ratios	10X,6E10.0
4	List of initial air temperatures	10X,6E10.0
5	List of temperature rise data corresponding to the fuel-air ratios and the initial air temperatures.	10X,6E10.0
6	List of molecular weight data corresponding to the fuel-air ratios and the initial air temperatures.	10X,6E10.0
7	List of gammas corresponding to the fuel-air ratios and the initial air temperatures.	10X,6E10.0

TABLE II - VARIABLES IN GEØM NAMELIST

The key word GEØMETRY precedes the namelist data. This word is read in on a A10 format.

Variable	Type	Value Before Read	Definition & Comments
A1	R	1.23	Area of station 1 in sq. ft.
ASTAR	R	0.00753	Area of ejector throat, sq. ft.
AE	R	0.030121	Area of the ejector exit, sq. ft.
A2	R	1.2601	Area of station 2 in sq. ft.
A3	R	5.2414	Area of station 3 is sq. ft.
A5	R	2.8852	Area of station 5 in sq. ft.
DUMPLØS	L	FALSE	Calculate diffuser & dump losses if true
ETAF2	L	FALSE	Use a fraction, ETAMIX, of the ideal momentum at station 2 if true
ETAFE	L	FALSE	Use a fraction, ETAMIX, of the ideal ejector momentum if true
ETAMIX	R	0.0	Mixing efficiency
TTF	R	1300.0	Total tempera . e of ejector flow in °R
A2P	R	2.52	Area of station 2' in sq. ft.
ND	R	0.25	Dump loss parameter
CPR	R	0.51	Diffuser performance parameter
C_{DB}	R	0.0	Burner drag coefficient
η_c	R	1.0	Combustion efficienty

TABLE III - FLIGHT PARAMETERS

Card Order	Contents	Format
1	RANGE	A10
2	Number of Mach numbers (Max - 8) Number of altitudes (Max - 4) Number of fuel-air ratios (Max - 20)	3I10
3	List of Mach number	8E10.0
4	List of altitudes	4E10.0
5	List of fuel-air ratios	8E10.0

TABLE IV - ENGINE IDENTIFICATION DATA

Card Order	Contents	Format
1	PRØBLEM	A10
2	Job title and job code (For an ejector ramjet the job code is any integer less than or equal to 0. For a ramjet use any integer greater than 0.) (The job title can be any comment the user wishes to make)	12A6,I8
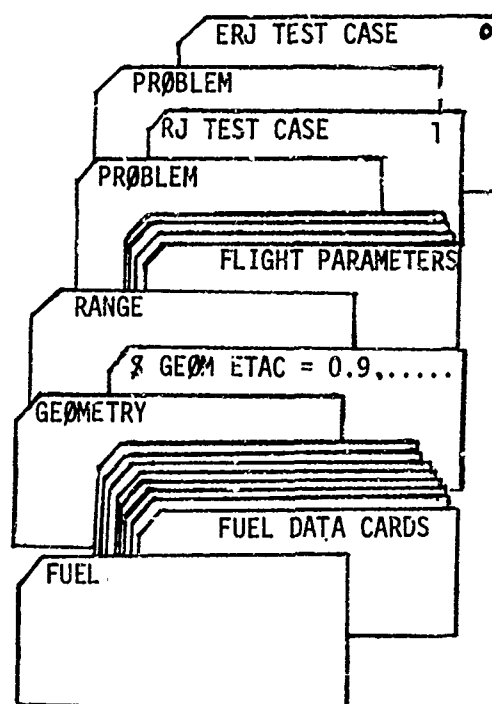
Figure 21. Typical Data Deck

MOMENTUM COMPRESSION RJ CHECKOUT.

AO	THRUST	Cf	ISP	SFC	FAR	AMO	ALT = 23000.0
.9401E+00	.3537E+03	.4499E+00	498.9458	7.2152	.0400	.50	
ADDITIVE DRAG	.3411E+03	.4339E+00	481.1822	7.4816			

STATION	0	1	2	3	4	5	E
Mach	.5000	.3558	.3909	.0893	.2280	.4506	2.4316
Gam			1.3837		1.2659		1.0689
Area-sq.ft.	.9401E+00	.1230E+01	.1260E+01	.5241E+01		.2885E+01	.3012E-01
Pres-ATM	.4051E+00	.4402E+00	.4395E+00	.4691E+00	.4565E+00	.4051E+00	.1518E+00
TOTP-ATM	.4805E+00		.4878E+00	.4717E+00	.4599E+00		.2694E+01
TOTT-°R	.459E+03		.5382E+03		.2834E+04		
Stream-LBF		1349.0719	1419.9204			3109.1281	70.8485
Mol Wt			29.352		28.514		

C.CJE = -.98159E-06   PO = .857244E+03   P5 = .357245E+03   WA = .1772E+02   WF = .7090E+00

Figure 22.   Sample Output

APPENDIX II

PROGRAM LISTING

```
          PROGRAM MOMCRJ (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)
          REAL ND
          EXTERNAL CYCLE, BUMAG, AINLET, BINLET
          LOGICAL DUMPLOS, RJ, TRAP, ETAF2, ETAFE
          DIMENSION AAMO(1), AALT(4), AFAR(20), TITLE(12)
          COMMON /CYCL/ A5, F5, RJ, TT4, GAM4, WTM4, TT0, ETAC
          COMMON /BUMA/ AM3, COB, M4P
          COMMON /ATNLT/ A1, AC, AE, ASTAR, AM0, AM1, AM3CK, DUMPLOS,
         1 ETAMIX, ETAF2, ETAFE, FAR, GAMT, INKT, P0, PT0, TC, TTF
          COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,ND
          NAMELIST/GEOM/ DUMPLOS, ETAF2, ETAFE, ETAMIX, TTF, A1, ASTAR,
         1 AE, A2, A3, A5, A2P,CPR, ND, COB, ETAC
          DATA FUE/4HFUEL/, GEO/8HGEOMETRY/, RANG/5HRANGE/,PROB/7HPROBLEM/
          ETAF2 = .FALSE.
          ETAFE = .FALSE.
          DUMPLOS = .FALSE.
          TTF = 1300.0
          A2P = 2.52
          ETAMIX = 1.0
          CPR = 0.51
          ND = 0.25
          COB = 0.0
          ETAC = 1.0
          A1 = 1.03
          ASTAR = 0.00753
          AF = 0.030121
          A2 = 1.2601
          A3 = 5.2414
          AE = 2.8852
          AMOLA = 1.0/28.966
    1     READ (5,2) WORD
    2     FORMAT (A10)
          WRITE (6,3) WORD
    3     FORMAT (1H A10)
          IF (WORD .EQ. FUE) GO TO 10
          IF (WORD .EQ. GEO) GO TO 20
          IF (WORD .EQ. RANG)  GO TO 111
          IF (WORD .EQ. PROB)  GO TO 701
          WRITE (6,25)
   25     FORMAT (10H STOP PROB)
          GO TO 1000
   10     CALL FUELDAT(0.0, 0.0, 0.0, 0.0, 0.)
          GO TO 1
   20     READ (5,GEOM)
          GO TO 1
  111     READ (5,1110) NUMAMO, NUMALT, NUMFAR
 1110     FORMAT (3I10)
          READ (5,700) (AAMO(I), I=1,NUMAMO)
          READ (5,700) (AALT(I), I=1,NUMALT)
          READ (5,700) (AFAR(I), I=1,NUMFAR)
          GO TO 1
  700     FORMAT (8E10.0)
  701     READ (5,112) (TITLE(I), I=1,12), ICODE
  112     FORMAT (12A6, I8)
          IF (EOF(5)) 1000, 1002
```

```
      1002  CONTINUE
            RJ = .FALSE.
            IF (ICODE .GT. 0)  RJ = .TRUE.
            DO 705  J1 = 1, NUMALT
            ALT = AALT(J1)
            CALL ATMOS (ALT, T0, DADSL, RHO, TATSL, PAPSL, C, VIS, 1)
            P0 = PAPSL*144.0*14.696
            DO 705  J2=1,NUMAMO
            AMO = AAMO(J2)
            TT0 = T0*TR(1.4, AMO)
            WRITE (6,13)
        13  FORMAT (1H0 13(10H*   *   * ))
            PT0 = P0*(1.0 + 0.2*(AMO**2))**3.5
            IF (RJ)  GO TO 15
            TTHRAT = TTF*0.83/1.8
            CALL PROPAN (TTHRAT, CPF, HFAKF)
            GAMT = CPF/(CPF - 1.987)
            TC= TTF/1.8
            CALL PROPAN (TC, CPC, HTF)
            TAIR = T0/1.8
            CALL AIRTHP (TAIR, CPA, HAIR)
            HTA = HAIR + (28.966*(C*AMO)**2)/(2.0*32.2*778.16*1.8)
        15  DO 705  J3=1,NUMFAR
            FAR = AFAR(J3)
            CALL FUELINT (TT0, FAR, DT, HTH4, GAM4)
            TT4 = TT0 + ETAC*DT
            IF (RJ) GO TO 498
            AMOLF = FAR/44.0
            TK2 = 350.0
            HT2 = (AMOLA*HTA + AMOLF*HTF)/(AMOLA + AMOLF)
            DO 201  I=1,3
            CALL PROPAN (TK2, CPF, H)
            CALL AIRTHR (TK2, CPA, H1)
            CP = (AMOLA*CPA + AMOLF*CPF)/(AMOLA + AMOLF)
            TK2CK = HT2/CP + 300.0
            TCHEK = TK2CK - TK2
        201 TK2 = TK2CK
            TT2 = TK2*1.8
            AWT = (1.0 + FAR)/(AMOLA + AMOLF)
            GAM2 = CP/(CP - 1.987)
        498 ACLOW = 0.1*A3
            IF (.NOT. RJ)  GO TO 489
            A1 = A2
            AWT = 28.966
            TT2 = TT0
            GAM2 = 1.4
        489 ACHIGH = A1
            X5 = X(GAM4, 1.0)
            X4 = X5*A5/A3
            AM4 = XM(X4, GAM4)
            Z4=Z(GAM4, AM4)
            Y4 = Y(GAM4, AM4)
            Y4P = Y4*SQRT(HTM4*TT2/(AWT*TT4*GAM2))
            IF (RJ) Y4P = Y4P/(1.0+FAR)
            CALL SOLNEW (BUMAC, 0.0, AM4, TRAP, Y1)
```

```
         AM3 = Y1
         ACT = A3*X(1.4,AM3)/X(1.4,AM0)
         IF (RJ) GO TO36
         INKT = 0
         ACH = A1
         ACL = A1/2.0
         CALL SOLNEW (BINLET, ACH, ACL, TRAP, Y1)
         IF (.NOT. TRAP) GO TO 460
         WRITE (6,34)
34       FORMAT (20HOBINLET - TRAP= TRUE)
         GO TO 240
460      ACMAX =AC
         ACL = 0.75*ACT
         IF (ACL .GT. ACMAX) ACL = 0.75*ACMAX
         INKT = 5
         CALL SOLNEW(AINLET, ACMAX, ACL, TRAP, Y1)
         IF (.NOT. TRAP)  GO TO 17
         WRITE (6,35)
35       FORMAT (13H TRAP IS TRUE)
         GO TO 240
17       IF (INKT .GT. 1)  GO TO 37
         IF ( AM3CK .GE. AM3) GO TO 37
         ACHIGH = ACMAX
         GO TO 499
36       PT3 = PT0
37       Z3 = Z(GAM2, AM3)
         PT4=PT3*(Z3/Z4-0.5*COB*GAM2*AM3**2/(Z4*PR(GAM2,AM3)))
         P5 = PT4/PR(GAM4,1.0)
         IF (.NOT. RJ) ACT = AC
         IF (P5 .LT. P0)  GO TO 497
         CALL CYCLE (ACT)
         GO TO 240
497      ACHIGH = ACT
499      CALL SOLNEW (CYCLE, ACLOW, ACHIGH, TRAP, YNEW)
         IF (.NOT. TRAP) GO TO 240
         WRITE (6,500)
500      FORMAT ( 1H0, 5X, 11HTRAP = TRUE)
240      Z0 = Z(1.4, AM0)
         F0 = PT0*AC*Z0
         Z1 = Z(1.4,AM1)
         F1 = PT0*A1*Z1
         THRUST = F5 - F0 - P0*(A5-AC)
         THRUSTN = F5 - F1 -P0*(A5-A1)
         FISP = THRUST/WF
         FISPN = THRUSTN/WF
         SFC = 3600.0/FISP
         SFCN = 3600.0/FISPN
         DEN = 0.5*1.4*P0*A3*AM0**2
         CF = THRUST/DEN
         CFN = THRUSTN/DEN
         WRITE (6,300) (TITLE(I), I=1,12), ALT, AC, THRUST, CF, FISP,
     2  SFC, FAP, AM0, THRUSTN, CFN, FISPN, SFCN
300      FORMAT(1H0/1H012A6,15X,4HALT=,F10.1/1H 8X,2HA0,12X,5HTHRUST,
     1  11X, 2HCF, 13X, 3HISP, 12X, 3HSFC, 14X, 3HFAP, 12X, 3HAM0/
     2  1H 3515.4,3F15.4,F15.2/14H ADDITIVE DRAG,2E15.4,3F15.4)
```

```
        FUN = HCYCLE (0.0)
 705    CONTINUE
        GO TO 1
 1000   STOP
        END
```

```
         FUNCTION CYCLE (ROOT)
         LOGICAL RJ, NSOL, DUMPLOS, ETAF2, ETAFE
         COMMON /CYCL/ A5, F5, RJ, TT4, GAM4, WTM4, TT0, ETAC
         COMMON /BUMA/ AM3, COB, Y4P
         COMMON /AINLT/ A1, AC, AE, ASTAR, AM0, AM1, AM3CK, DUMPLOS,
        1 ETAMIX, ETAF2, ETAFE, FAR, GAMT, INKT, P0, PT0, T0, TTF
         COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,NO
1        AC = ROOT
         X1 = AC*X(1.4, AM0)/A1
         AM1 = XM(X1, 1.4)
         P1 = PT0/PR(1.4,AM1)
         WA = P0*AC*AM0*SQRT((1.4*32.2*28.966)/(1545.264*T0))
         FA1 = PT0*A1*Z(1.4, AM1)
         WF = WA*FAR
         IF (.NOT. RJ) GO TO 5
         AM2 = AM1
         F2 = FA1
         GO TO 52
5        XSTAR = X(GAMT, 1.0)
         PTP = (WF*SQRT((TTF*1545.264)/(32.2*44.0)))/(ASTAR*XSTAR)
         PTH = PTP/PR(GAMT, 1.0)
         IF(PT4.LT.P1) GO TO 10
         XE = XSTAR*ASTAR/AE
         AME = SMX (XF, GAMT)
         FE = PTP*AE*Z(GAMT, AME)
         GO TO 15
10       AME=WF/(P1*AE*SQRT(GAMT*32.2*44./(1545.264*TTF)))
         FE = P1*AE*(1.0+GAMT*(AME**2))
         PTP = P1*PR(GAMT, AME)
15       F2 = FA1 + FE
         IF(ETAF2)  F2= ETAMIX*F2
         IF (ETAFE)  F2 = FA1 + ETAMIX*FE
         Y2 = ((WA + WF)*SQRT(TT2*1545.264/(32.2*AWT)))/F2
50       AM2 = YM(Y2, GAM2)
52       Z2 = Z(GAM2,AM2)
         X2 = X (GAM2, AM2)
         IF (RJ) GO TO 56
         IF (DUMPLOS)  GO TO 57
56       X3 = X2*A2/A3
         PT3 = ((WA+WF)*SQRT(TT2*1545.264/(32.2*AWT)))/(A3*X3)
         IF(RJ) PT3=(WA*SQRT(TT2*1545.264/(32.2*AWT)))/(A3*X3)
         GO TO 58
57       CALL DUMP  (Z2, X3)
58       AM3 = XM (X3, GAM2)
         Y3 = Y (GAM2, AM3)
         Z3 = Z (GAM2, AM3)
         P3 = PT3/PR(GAM2,AM3)
         P3ATM = P3/(144.0*14.696)
70       Y4 =Y3*SQRT(AWT*TT4/(WTM4*TT2))
         Y4 = Y4*(1.0 + GAM2*AM3**2)/(1.0+GAM2*AM3**2*(1.0-0.5*COB))
         IF (RJ) Y4 = Y4*(1.0+FAR)
         AM4 = YM(Y4, GAM4)
         X4 = X(GAM4, AM4)
         X5 = X4*A3/A5
         AM5 = YM(X5, GAM4)
```

```
ION    CYCLE                                      CDC 6600 FTN V3.0-251A OPT=1  07/15/71

          Z4 = Z(GAM4, AM4)
          PT4 = PT3*(Z3/Z4 - 0.5*COB*GAM2*AM3**2/(Z4*PR(GAM2,AM3)))
          P5 = PT4/PR(GAM4,AM5)
          Z5 = Z(GAM4, AM5)
          F5 = A4*A5*Z5
          CYC = 1.0 - P5/P0
          GO TO 300
          ENTRY WCYCLE
          PT2A = F2/(A2*Z2*2116.224)
          P2 = PT2A/PR(GAM2,AM2)
          P4 = PT3/(2116.224*PR(GAM4,AM4))
          P0ATM = P0/2116.224
          P5ATM = P5/2116.224
          PT0A = PT0/2116.224
          P1 = P1/2116.224
          PT3A = PT3/2116.224
          PT4A = PT4/2116.224
          IF (RJ) GO TO 200
          PTPA = PTP/2116.224
          PEA = PTPA/PR(GAMT,AME)
  200     WRITE (6,250) AM0, AM1, AM2, AM3, AM4, AM5, AME, GAM2, GAM4,
         1 GAMT, AC, A1, A2, A3, A5, AE, P0ATM, P1, P2, P3ATM, P4, P5ATM,
         2 PEA, PT0A, PT2A, PT3A, PT4A, PTPA, TT0, TT2, TT4, FA1, F2, F5,
         3 FE, AWT, WTM4
  250     FORMAT(8H0STATION, 9X, 1H0, 15X, 1H1, 15X, 1H2, 15X, 1H3, 15X,
         1 1H4, 15X, 1H5, 15X, 1HE/ 5H MACH, F15.4, 6F16.4/ 4H GAM, 32X,
         2 F16.4, 16X, F16.4, 16X, F16.4/ 5H AREA, 2X, 4E16.4, 16X,
         3 2E16.4/ 5H PRES, 2X, 7E16.4/ 5H TOTP, 2X, E16.4, 15X, 3E16.4,
         4 16X, F16.4/ 5H TOTT, 2X, E16.3, 16X, E16.4, 16X, E16.4,
         5 / 7H STREAM, 16X, 2F16.4, 32X, F16.4,        F15.4/ 7H MOL WT,
         5 38X, F7.3, 28X, F7.3)
          WRITE (6,252) CYCLE, P0, P5, WA, WF
  252     FORMAT (7H CYCLE=, E13.6, 5X, 3HP0=, E13.6, 5X, 3HP5=, E13.6, 5X,
         1 3HWA=, E11.4, 5X, 3HWF=, E11.4)
   30     RETURN
          END
```

62

```
ION     AINLET                              CDC 6600 FTN V3.0-251A  OPT=1   07/15/7:

            FUNCTION AINLET(A)
            LOGICAL   DUMPLOS, ETAF2, ETAFE,ACLOG
            COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,ND
            COMMON /BUMA/ AM3, CDB, Y4P
            COMMON /AINLT/ A1, AC, AE, ASTAR, AM0, AM1, AM3CK, DUMPLOS,
           1 ETAMIX, ETAF2, ETAFE, FAR, GAMT, INKT, P0, PT0, IO, TTF
            ACLOG = .FALSE.
            GO TO 1
            ENTRY BINLET
            ACLOG = .TRUE.
      1     AC=A
            INKT = INKT + 1
            X1 = AC*X(1.4,AM0)/A1
            AM1= XM(X1,1.4)
            P1 = PT0/PR(1.4,AM1)
            WA = P0*AC*AM0*SQRT((1.4*32.2*28.966)/(1545.264*T0))
            FA1 = PT0*A1*Z(1.4,AM1)
            WF = WA*FAR
            XSTAR = X(GAMT, 1.0)
            PTP = (WF*SQRT((TTF*1545.264)/(32.2*44.0)))/(ASTAR*XSTAR)
            PTH = PTP/PR(GAMT, 1.0)
            IF (PTH.LT.P1) GO TO 3
            XE = XSTAR*ASTAR/AE
            AME = SMX(XE,GAMT)
            FE = PTP*AE*Z(GAMT, AME)
            GO TO 4
      3     AME=WF/(P1*AE*SQRT(GAMT*32.2*44./(1545.264*TTF)))
            FE = P1*AE*(1.0+GAMT*(AME**2))
      4     F2 = FA1 + FE
            IF(ETAF2)  F2= ETAMIX*F2
            IF (ETAFE)  F2 = FA1 + ETAMIX*FE
            Y2 =((WA+WF)*SQRT(TT2*1545.264/(32.2*AWT)))/F2
            IF (.NOT. ACLOG) GO TO 10
            YCK = Y(GAM2, 1.0)
            AINLET = (1.0 -Y2/YCK)
            IF ((AINLET .GE. 0.0) .AND. (INKT .EQ. 1)) AINLET=0.0
            AINLET = AINLET*1.0E3
            GO TO 500
      10    AM2 = YM(Y2,GAM2)
            Z2 = Z(GAM2, AM2)
            X2 = X(GAM2, AM2)
            IF (DUMPLOS)  GO TO 5
            X3 = X2*A2/A3
            PT3 = ((WA+WF)*SQRT(TT2*1545.264/(32.2*AWT)))/(A3*X3)
            GO TO 6
      5     CALL DUMP (Z2, X3)
      6     AM3CK = XM(X3, GAM2)
            AINLET = (AM3 - AM3CK)/AM3
            IF ((AINLET .GE. 0.0) .AND. (INKT .EQ. 1)) AINLET=0.0
            AINLET = AINLET*1.0E2
      500   RETURN
            END
```

```
      SUBROUTINE DUMP (Z2, X3)
C  COMPUTES DIFFUSER AND DUMP LOSSES
      COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,DND
      PT2 = F2/(A2*Z2)
      P2 = PT2/PR(GAM2,AM2)
      P3 = (0.5*CPR*GAM2*(AM2**2) + 1.0)*P2
      AONE = (GAM2-1.0)/2.0
      CONE = -(((WA+WF)**2)*1545.264*TT2)/((P3**2)*(A2P**2)*(GAM2*32.2
     1 *AWT))
      Q = SQRT(1.0-4.    NE*CONE)
      AM3P = (-1.0+Q)/(2.  AONE)
      IF((AM3P.LE.0.).OR.(AM3P.GE.1.))  AM3P = (-1.0-Q)/(2.0*AONE)
      AM3P = SQRT(AM3P)
      PT3 = P3*PR(GAM2,AM3P)
      PT3 = PT3*EXP(-0.5*DND*GAM2*AM3P**2)
      X3 = (WA+WF)*SQRT(1545.264*TT2/(32.2*AWT))/(PT3*A3)
      RETURN
      END
```

```
(OV    BUMAC                                      CDC 6600 FTN V3.0-251A OPT=1  07/15/71

       FUNCTION BUMAC(A)
       COMMON /BUMA/ AM3, CDB, Y4P
       COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,ND
       AM3 = A
       SQ = A**2
       BUMAC = Y4P*(1.0+GAM2*SQ*(1.0-CDB/2.0))/(SQRT(1.0+(GAM2-1.0)/2.0
      1 *SQ)) - A
       BUMAC = BUMAC*1.0E2
       RFTURN
       END
```

UTINE PROPAN

```
      SUBROUTINE PROPAN (T, CP, HF)
      A = -0.966
      B = 7.279E-2
      C = -3.755E-5
      D = 7.58E-9
      CP = A + B*T + C*(T**2) + D*(T**3)
      TC = 300.0
      HCON = A*TC + 0.5*B*(TC**2) + C*(TC**3)/3.0 + 0.25*D*(TC**4)
      HF = A*T + 0.5*B*(T**2) + C*(T**3)/3.0 + 0.25*D*(T**4) - HCON
      RETURN
      END
```

```
      SUBROUTINE AIRTHR (T, CP, HA)
      A = 6.386
      B = 1.762E-3
      C = -2.656E-7
      CP = A + B*T + C*(T**2)
      TC = 300.0
      HCON = A*TC + 0.5*B*(TC**2) + C*(TC**3)/3.0
      HA = A*T + 0.5*B*(T**2) + C*(T**3)/3.0 - HCON
      RETURN
      END
```

```
      SUBROUTINE ATMOS(Z,TM,SIGMA,RHO,THETA,DELTA,CA,AMU,K)              ATMOS001
                                                                        ATMOS002
C     CALLING SEQUENCE                                                  ATMOS003
                                                                        ATMOS004
C     CALL ATMOS(Z,TM,SIGMA,RHO,THETA,DELTA,CA,AMU,K)                   ATMOS005
                                                                        ATMOS006
C     Z    = GEOMETRIC ALTITUDE (FT)                                    ATMOS007
C     TM   = MOLECULAR SCALE TEMPERATURE (DEGREES RANKIN)               ATMOS008
                                                                        
C     RHO  = DENSITY LB-SEC**2-FT**(-4) OR SLUGS-FT**3                  ATMOS010
C     THETA = RATIO OF TEMPERATURE TO THAT AT SEA LEVEL                 ATMOS011
C     DELTA = RATIO OF PRESSURE TO THAT AT SEA LEVEL                    ATMOS012
C     CA   = SPEED OF SOUND (FT/SEC)                                    ATMOS013
C     AMU  = VISCOSITY COEFFICIENT (LB-SEC-FT**2)                       ATMOS014
                                                                        ATMOS015
C     K = 1 NORMAL,                                                     ATMOS016
C       = 2 ALTITUDE GREATER THAN 300000. FT.,                         ATMOS017
C       = 3 ALTITUDE NEGATIVE,                                          ATMOS018
                                                                        ATMOS019
                                                                        ATMOS020
      DIMENSION HPRIMB(11),TMB(11),SIGMAB(11),ALM(11),ARAY(11,4)        ATMOS021
      EQUIVALENCE (ARAY(1,1),HPRIMB(1)),(ARAY(1,2),TMB(1)),             ATMOS022
     *            (ARAY(1,3),SIGMAB(1)),(ARAY(1,4),ALM(1))              ATMOS023
                                                                        ATMOS024
      DATA ((ARAY(I,J),J=1,4),I=1,11)/                                  ATMOS025
     X          0.    ,      518.688 ,   1.0000000E 00 ,  -0.00356616 , ATMOS0 6
     X      36089.239 ,      389.988 ,   2.9706958E-01 ,   0.         , ATMOS027
     X      62020.997 ,      389.988 ,   3.2665751E-02 ,   0.00164592 , ATMOS028
     X     154199.480 ,      508.788 ,   1.2117870E-03 ,   0.         , ATMOS029
     X     173884.510 ,      508.788 ,   5.8677311E-04 ,  -0.00246888 , ATMOS0 0
     X     259186.350 ,      298.188 ,   1.7329156E-05 ,   0.         , ATMOS031
     X     295275.590 ,      298.188 ,   1.7928595E-06 ,   0.00219456 , ATMOS032
     X     344498.190 ,      406.198 ,   9.3921519E-08 ,   0.01097280 , ATMOS0 3
     X     524974.380 ,     2386.198 ,   7.7658593E-10 ,   0.00548640 , ATMOS034
     X     557742.780 ,     2566.188 ,   5.6324877E-10 ,   0.00274320 , ATMOS0
     X     656167. 80 ,     2836.188 ,   2.5726771E-10 ,   0.001 2024 / ATMOS036
      DATA  Q    /  0.01874 176    / ,   RE  /  2.0855531E 07    / ,    ATMOS038
     X      S    /  198.72         / ,   PZ  /  2116.2           / ,    ATMOS0 9
     X      AMUZ /  3.7372999E-07  / ,  RHOZ /  0.0023769        / ,    ATMOS040
     X      TMZ  /  518.688        /                                    ATMOS041
      K=1
      IF(Z)26,18,17
  26  K=3
      GO TO 13
  17  IF(Z.GT.300000.)  K=K+1
  18  HPRIM=(RE/(RE+Z))*Z
   9  DO 10 M=1,11
      IF(HPRIM-HPRIMB(M))11,12,10
  10  CONTINUE
      M=12
  11  M=M-1
  12  IF(ALM(M))14,15,14
  14  TM=TMB(M)+ALM(M)*(HPRIM-HPRIMB(M))
      SIGMA=EXP((1.0+(Q/ALM(M)))*(ALOG(TMB(M)/TM)))*SIGMAB(M)
      GO TO 20
```

```
UTINE  ATMOS                                          CDC 6600 FTN V3.0-251A OPT=1  07/15/71
      15    TM=TMB(M)
            SIGMA=SIGMAB(M)*EXP(-(Q*(HPRIM-HPRIMB(M))'/TMB(M))
      20    RHO=RHOZ*SIGMA
            THETA=TM/TMZ
            DELTA=SIGMA*THETA
            CA=49.02177*SQRT(TM)
            AMU=AMUZ*SQRT(THETA**3)*((TMZ+S)/(TM+S))               ATMOS064
      13    RETURN                                                 ATMOS065
            END                                                    ATMOS066
```

```
        FUNCTION ATKN(X,Y,N,K,XI)                               ATKN00°1
C                                                               ATKN0002
C       ATKN      AITKEN INTERPOLATING FUNCTION                 ATKN0093
C                                                               ATKN0014
C       USAGE...                                                ATKN0015
C                                                               ATKN6006
C       Z=ATKN(X,Y,N,K,XI)                                      ATKN00°7
C                                                               ATKN0038
C         WHERE...                                              ATKN0009
C                                                               ATKN0010
C         X - TABLE OF INDEPENDENT VARIABLE VALUES,             ATKN0011
C             (MAY BE ASPENDING OR DESCENDING).                 ATKN0012
C         Y - TABLE OF DEPENDENT VARIABLE VALUES.               ATKN0013
C         N - NO. OF POINTS IN TABLES X AND Y.                  ATKN0014
C         K - DEGREE OF INTERPOLATION DESIRED.                  ATKN0015
C         XI- X-VALUE FOR WHICH INTERPOLATION IS DESIRED.       ATKN0016
C                                                               ATKN0017
C         THE INTEPOLATED VALUE IS RETURNED AS THE FUNCTION VALUE.  ATKN0018
C                                                               ATKN0019
C         31 CELLS OF BLANK COMMON ARE USED.                    ATKN00_0
C                                                               ATKN00_1
        DIMENSION   X(N), Y(N)                                  ATKN00:2
        COMMON    I1, K1, LI, LL, LU                            ATKN00°3
        COMMON    XX(13), YY(13)                                ATKN00 4
        DATA    KMAX/ 12/                                       ATKN00°5
C                                                               ATKN00?6
        IF ( K .GT. KMAX .OR. K .LE. 0 )      GO TO 300         ATKN0027
C                                                               ATKNC0 8
        K1=K+1                                                  ATKN00?9
        IF (X(N)-X(1)) 100,10,10                                ATKN00 0
     10 IF (XI-X(1)) 20,20,30                                   ATKN00 1
     20 LL=0                                                    ATKN00 2
        GO TC 200                                               ATKN00 3
     30 IF (X(N)-XI) 40,40,50                                   ATKN00 4
     40 LL=N-K1                                                 ATKN00 5
        GO TO 200                                               ATKN00 6
     50 LL=1                                                    ATKN00 7
        LU=N                                                    ATKN00 8
     60 IF (LU-LL-1) 180,180,70                                 ATKN00 9
     70 LI=(LL+LU)/2                                            ATKN00+0
        IF (X(LI)-XI) 80,80,90                                  ATKN0041
     80 LL=LI                                                   ATKN00 2
        GO TO 60                                                ATKN00 3
     90 LU=LI                                                   ATKN0044
        GO TO 60                                                ATKN00 5
    100 IF (XI-X(1)) 120,20,20                                  ATKN0046
    120 IF (X(N)-XI) 130,40,40                                  ATKN00 7
    130 LL=1                                                    ATKN00 8
        LU=N                                                    ATKN0049
    140 IF (LU-LL-1) 180,180,150                                ATKN0050
    150 LI=(LL+LU)/2                                            ATKN0051
        IF (Y(LI)-XI) 160,170,170                               ATKN0052
    160 LU=LI                                                   ATKN0053
        GO TO 140                                               ATKN00 4
    170 LL=LI                                                   ATKN0055
```

```
          GO TO 140                                           ATKN0056
      180 LL=LL-(K1+1)/2                                      ATKN0057
          IF (LL) 20,200,190                                  ATKN0058
      190 IF (LL+K1-N) 200,200,40                             ATKN0059
      200 DO 210 I=1,K1                                       ATKN0060
          I1=LL+I                                             ATKN0061
          XX(I)=X(I1)-XT                                      ATKN0062
      210 YY(I)=Y(I1)                                         ATKN0063
          DO 220 I=1,K                                        ATKN0064
          DO 220 J=I,K                                        ATKN0065
      220 YY(J+1)=(1./(XX(J+1)-XX(I)))*(YY(I)*XX(J+1)-YY(J+1)*XX(I))   ATKN0066
          ATKN=YY(K1)                                         ATKN0057
          RETURN                                              ATKN0068
    C                                                         ATKN0069
      700 PRINT 1000, K                                       ATKN0070
     1000 FORMAT (?HOK=,I12,?7H   IS INCORRECT FOR FUNCTION ATKN)   ATKN0071
          CALL SYSTEM(200.0)                                  ATKN0072
          END                                                 ATKN0073
```

```
        SUBROUTINE SOLNEW(FX, ALOW, HI, TRAP, Y)              SOL   1
C  SOLVES THE FUNCTION FX FOR THE VALUE OF THE INDEPENDENT VARIABLE X   SOL   2
C  WHICH MAKES THE VALUE OF FX EQUAL TO ZERO.  THE VALUE OF X MUST LIE  SOL   3
C  IN THE INTERVAL BOUNDED BY ALOW AND HI.  IF ANY FATAL DIFFICULTY IS  SOL   4
C  INCOUNTERED IN THE SOLUTION THE LOGICAL VARIABLE TRAP IS SET EQUAL   SOL   5
C  TO TRUE.                                                             SOL   6
        EXTERNAL FX                                            SOL   7
        LOGICAL TRAP, FIRST
        DIMENSION F(4), X(4)                                   SOL   9
        TRAP = .FALSE.                                         SOL  10
        FIRST = .TRUE.
        TOL = 1.0E-4
        H = HI                                                 SOL  12
        SMAL = ALOW                                            SOL  13
        IF (ALOW .LT. HI) GO TO 17                             SOL  14
        H = ALOW                                               SOL  15
        SMAL = HI                                              SOL  16
17      X(1) = ALOW                                            SOL  17
        F(1) = FX(X(1))                                        SOL  18
        Y = X(1)                                               SOL  19
        IF (ABS(F(1)) .LT. TOL)  GO TO 83                      SOL  20
        X(3) = HI                                              SOL  21
        F(3) = FX(X(3))                                        SOL  22
        Y = X(3)                                               SOL  23
        IF (ABS(F(3)).LT. TOL)  GO TO 83                       SOL  24
        Z = SIGN(F(1), F(3))                                   SOL  25
        IF ((F(1)+Z) .EQ. 0.0)  GO TO 32                       SOL  26
        WRITE (6,28)                                           SOL  27
28      FORMAT (60H THE FUNCTIONS FOR THE END POINTS DO NOT HAVE OPPOSITE
       1SIGNS)
        TRAP = .TRUE.                                          SOL  30
        GO TO 83                                               SOL  31
32      X(2) = X(1) - F(1)*(X(3) - X(1))/(F(3)- F(1))          SOL  32
        F(2) = FX(X(2))                                        SOL  33
        Y = X(2)                                               SOL  34
        IF (ABS(F(2)) .LT. TOL)  GO TO 83                      SOL  35
        DO 69  JK=1,9                                          SOL  36
        X1SQ = X(1)**2                                         SOL  37
        X1X2 = X(1) - X(2)                                     SOL  38
        X1X3 = X(1) - X(3)                                     SOL  39
        X2X1SQ = X(2)**2 - X(1)**2                             SOL  40
        A = X1X3*(F(2)-F(1)) - X1X2*(F(3)-F(1))                SOL  41
        A = A/(X1X3*X2X1SQ - X1X2*(X(3)**2 - X1SQ))            SOL  42
        B = (A*X2X1SQ - F(2) + F(1))/X1X2                      SOL  43
        C = F(3) - A*(X(3)**2) - B*X(3)                        SOL  44
        Q = SQRT(B**2 - 4.0*A*C)                               SOL  45
        X(4) = (-B+Q)/(2.0*A)                                  SOL  46
        IF((X(4).GT.H).OR.(X(4).LT.SMAL)) X(4)=(-B-Q)/(2.0*A)  SOL  47
        Y = X(4)                                               SOL  48
        IF (JK .EQ. 9) GO TO 70                                SOL  49
        F(4) = FX(X(4))                                        SOL  50
        IF (ABS(F(4)) .LT. TOL)  GO TO 83                      SOL  51
        DO 62  I=1,3                                           SOL  52
        I1 = I+1                                               SOL  53
        DO 62  J=I1,4                                          SOL  54
```

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UTINE SOLNEW   CDC 6600 FTN V3.0-251A OPT=1   07/15/71

```
              IF (F(I) .LE. F(J))  GO TO 62                    SOL  55
              FS = F(I)                                        SOL  56
              XS = X(I)                                        SOL  57
              F(I) = F(J)                                      SOL  58
              X(I) = X(J)                                      SOL  59
              F(J) = FS                                        SOL  60
              X(J) = XS                                        SOL  61
    62        CONTINUE                                         SOL  62
              IF (.NOT. FIRST)  GO TO 63
              IF ((F(1) + F(2)) .LE. F(1))  GO TO 100
              XN = (2.0*X(2) + X(1))/3.0
              FN = FY(XN)
              IF ((F(1) + FN) .LE. F(1))  GO TO 110
              F(2) = FN
              X(2) = XN
              GO TO 63
    100       IF ((F(3) + F(4)) .GE. F(4))  GO TO 63
              XN = (X(4) + 2.0*X(3))/3.0
              FN = FX(XN)
              IF ((F(4) + FN) .GE. F(4))  GO TO 115
              F(3) = FN
              X(3) = XN
              GO TO 63
    110       F(1) = FN
              X(1) = XN
              GO TO 63
    115       F(4) = FN
              X(4) = XN
    63        FIRST = .FALSE.
              IF (ABS(F(1)) .GT. ABS(F(4)))  GO TO 68          SOL  63
              IF ((F(3)+F(4)) .GE. F(4))  GO TO 69             SOL  64
    65        F(1) = F(4)                                      SOL  65
              X(1) = X(4)                                      SOL  66
              GO TO 69                                         SOL  67
    68        IF ((F(1)+F(2)) .LE. F(1))  GO TO 65             SOL  68
    69        CONTINUE                                         SOL  69
    70        DO 82   I=1,5                                    SOL  70
              FY = FX(Y)                                       SOL  71
              IF (ABS(FY) .LT. TOL)  GO TO 83                  SOL  72
              XLIT = Y + 0.01*TOL*Y                            SOL  73
              FLIT = FX(XLIT)                                  SOL  74
              XD = Y - XLIT                                    SOL  75
              FD = FY- FLIT                                    SOL  76
              DIR = FD/XD                                      SOL  77
              IF (DIR .NE. 0.0)  GO TO 81                      SOL  78
              TRAP = .TRUE.                                    SOL  79
              GO TO 83                                         SOL  80
    81        Y = Y - FY/DIR                                   SOL  81
    82        CONTINUE                                         SOL  82
              WRITE (6,85)
    85        FORMAT (24H SOLNEW DID NOT CONVERGE)
              TRAP = .TRUE.
    83        RETURN                                           SOL  83
              END                                              SOL  84
```

```
      FUNCTION  X(G, A)                                            X   1
C  DETERMINES  X  AS A FUNCTION OF MACH NUMBER.   G=GAMMA, A=MACH NO.    X   2
      G1 = G - 1.0                                                 X   3
      X = A*SQRT(G/((1.0+0.5*G1*(A**2))**((G+1.0)/G1)))            X   4
      RETURN                                                       X   5
      END                                                          X   6
```

```
      FUNCTION  Y(G, A)                                        Y    1
C  DETERMINES  Y  AS A FUNCTION OF MACH NUMBER.  G=GAMMA, A=MACH NO.   Y    2
      SQ = A**2                                                Y    3
      Y = (A/(1.0+G*SQ))*SQRT(G*(1.0+0.5*(G-1.0)*SQ))          Y    4
      RETURN                                                   Y    5
      END                                                      Y    6
```

```
        FUNCTION  Z(G, A)                                            Z    1
C  DETERMINES  Z  AS A FUNCTION OF MACH NUMBER.  G=GAMMA, A=MACH NO.   Z    2
        SQ = A**2                                                    Z    3
        G1 = G - 1.0                                                 7    4
        Z = (1.0+G*SQ)/((1.0+0.5*G1*SQ)**(G/G1))                     Z    5
        RETURN                                                       Z    6
        END                                                         Z    7
```

```
          SUBROUTINE FUELDAT (TO, FAR, DT, WTH4, GAM4)
          DIMENSION TEMS(12), FARS(18), Z1(18,12), Z2(18,12), Z3(18,12)
          READ (5,2)  NFAR, NT
    2     FORMAT (2I10)
          READ (5,5) (FARS(I), I=1,NFAR)
          READ (5,5)  (TEMS(I), I=1,NT)
    5     FORMAT (10X, 6E10.0)
          DO 10  K=1,NT
   10     READ (5,5)  (Z1(I,K) I=1,NFAR)
          DO 20  K=1,NT
   20     READ (5,5)  (Z2(I,K), I=1,NFAR)
          DO 30  K=1,NT
   30     READ (5,5)  (Z3(I,K), I=1,NFAR)
          RETURN
          ENTRY FUELINT
          DT   = BUYIN(FAR, TO, FARS, NFAR, TEMS, NT, Z1)
          WTH4 = BUYIN(FAR, TO, FARS, NFAR, TEMS, NT, Z2)
          GAM4 = BUYIN(FAR, TO, FARS, NFAR, TEMS, NT, Z3)
          RETURN
          END
```

```
[ON    BUYIN                    . . . . . .              CDC 6600 FTN V3.0-251A OPT=1   07/15/7:
       FUNCTION BUYIN (XI, YI, X, NX, Y, NY, Z)
       DIMENSION X(18), Y(12), Z(18,12), V(18), U(12)
       DO 6  I=1,NY
       DO 5  J=1,NX
    5  V(J) = Z(J,I)
    6  U(I) = ATKN (X, V, NX,  1, XI)
       BUYIN = ATKN (Y, U, NY, 1, YI)
       RETURN
       END
```

```
        FUNCTION XM(X,G)                                              XM    1
      C DETERMINES SUBSONIC MACH NUMBER AS A FUNCTION OF X.  G=GAMMA   XM    2
        TOL = X*1.0E-8
        G1 = G-1.0                                                     XM    4
        XM = 0.0                                                       XM    5
        F1 = -X                                                        XM    6
        IF(ABS(F1) .LE. TOL)  GO TO 26                                 XM    7
        XM = 1.0                                                       XM    8
        F3 = SQRT(G/((1.0+0.5*G1)**((G+1.0)/G1))) - X                  XM    9
        IF(ABS(F3) .LT. TOL)  GO TO 26                                 XM   10
        SI = SIGN(F1, F3)
        IF ((F1 + SI) .EQ. 0.0) GO TO 13
        PRINT 100, F3
  100   FORMAT (30H SAME SIGN FOR X FUNCTION - F=, E13.5)
        XM = 1.0
        GO TO 26
   13   XM =-F1/(F3 - F1)                                              XM   11
        F2 = XM*SQRT(G/((1.0+0.5*G1*(XM**2))**((G+1.0)/G1))) - X       XM   12
        A = ((F3-F1)*XM - F2 + F1)/(XM*(1.0-XM))
        B = F3 - F1 - A                                                XM   14
        C = F1                                                         XM   15
        RT = SQRT(B**2 - 4.0*A*C)                                      XM   16
        XM = (-B+RT)/(2.0*A)                                           XM   17
        IF((XM.GT.1.0) .OR. (XM.LT.0.0)) XM=(-B-RT)/(2.0*A)            XM   18
        DO 25  I=1,9
        SQ = XM**2                                                     XM   20
        F = XM*SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))) - X            XM   21
        IF(ABS(F) .LT. TOL) GO TO 26                                   XM   22
        FP = 2.0*(1.0-SQ)*(SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))))    XM   23
       1 /(2.0 + G1*SQ)                                                XM   24
   25   XM = XM - F/FP                                                 XM   25
        PRINT 50
   50   FORMAT (23H X FUN DID NOT CONVERGE)
   26   RETURN                                                        XM   26
        END                                                           XM   27
```

```
        FUNCTION YM(Y,G)                                              YM     1
C   DETERMINES SUBSONIC MACH NO. AS A FUNCTION OF Y.  G=GAMMA         YM     2
        TOL = Y*1.0E-8
        G1 = G - 1.0                                                  YM     4
        YM = 0.0                                                      YM     5
        F1 = -Y                                                       YM     6
        IF (ABS(F1) .LE. TOL) GO TO 27                               YM     7
        YM = 1.0                                                      YM     8
        F3 = (SQRT(G*(1.0+0.5*G1)))/(1.0+G) - Y                      YM     9
        IF (ABS(F3) .LT. TOL)  GO TO 27                              YM    10
        YM =-F1/(F3 - F1)                                            YM    11
        SQ = YM**2                                                   YM    12
        F2 = (YM/(1.0+G*SQ))*SQRT(G*(1.0+0.5*G1*SQ)) - Y            YM    13
        A = ((F3-F1)*YM - F2 + F1)/(YM*(1.0-YM))
        B = F3 - F1 - A                                             YM    15
        C = F1                                                      YM    16
        RT = SQRT(B**2 - 4.0*A*C)                                   YM    17
        YM = (-B+RT)/(2.0*A)                                        YM    18
        IF (YM.LT.0.0) .OR. (YM.GT.1.0)) YM=(-B-RT)/(2.0*A)        YM    19
        5    I=1,9
        SQ = YM**2                                                  YM    21
        F  (YM/(1.0+G*SQ))*SQRT(G*(1.0+0.5*G1*SQ)) - Y            YM    22
        IF (ABS(F) .LT. TOL) GO TO 27                               YM    23
        FP = ((1.0-SQ)/(1.0+0.5*G1*SQ))*(SQRT(G*(1.0+0.5*G1*SQ)))/  YM    24
       1 ((1.0+G*SQ)**2)                                            YM    25
  26    YM = YM - F/FP                                              YM    26
        PRINT 50
  50    FORMAT (23H Y FUN DID NOT CONVERGE)
  27    RETURN                                                      YM    27
        END                                                         YM    28
```

```
          FUNCTION ZM(Z,G)                                              ZM    1
C  DETERMINES SUBSONIC MACH NUMBER AS A FUNCTION OF Z.  G=GAMMA         ZM    2
          TOL = Z*1.0E-9
          G1 = G - 1.0                                                  ZM    4
          ZM = 0.0                                                      ZM    5
          F1 = 1.0 - Z                                                  ZM    6
          IF(ABS(F1) .LT. TOL)  GO TO 26                               ZM    7
          ZM = 1.0                                                      ZM    8
          F3 = (1.0+G)/((1.0+0.5*G1)**(G/G1)) - Z                       ZM    9
          IF(ABS(F3) .LT. TOL) GO TO 25                                 ZM   10
          ZM = F1/(F3 - F1)                                             ZM   11
          SQ = ZM**2                                                    ZM   12
          F2 = (1.0 + G*SQ)/((1.0+0.5*G1*SQ)**(G/G1)) - Z               ZM   13
          A = ((F3-F1)*ZM - F2 + F1)/(ZM-SQ)                            ZM   14
          B = F3 - F1 - A                                               ZM   15
          C = F1                                                        ZM   16
          RT = SQRT(B**2 - 4.0*A*C)                                     ZM   17
          ZM = (-B + RT)/(2.0*A)                                        ZM   18
          IF((ZM.GT.1.0).OR.(ZM.LT.0.0)) ZM=(-B-RT)/(2.0*A)            ZM   19
          DO 25  I=1,10                                                 ZM   20
          SQ = ZM**2                                                    ZM   21
          F = (1.0+G*SQ)/((1.0+0.5*G1*SQ)**(G/G1)) - Z                  ZM   22
          IF (ABS(F) .LT. TOL) GO TO 25                                 ZM   23
          FP=G*ZM*(2.-(1.+G*SQ)/(1.+.5*G1*SQ))/((1.+.5*G1*SQ)**(G/G1))  ZM   24
25        ZM = ZM - F/FP                                                ZM   25
          POINT 50
50        FORMAT (23H Z FUN DID NOT CONVERGE)
26        RETURN                                                        ZM   26
          END                                                          ZM   27
```

```
ION    SMX                                    CDC 6600 FTN V3.0-251A OPT=1   07/15/7'

         FUNCTION SMX(X,G)                                              SMX    1
C DETERMINES SUPERSONIC MACH NO. AS A FUNCTION OF X, G=GAMMA, MAX MACH=4 SMX    2
         DIMENSION  FA(3), XA(3)                                        SMX    3
         TOL = X*1.0E-5                                                 SMX    4
         G1 = G - 1.0                                                   SMX    5
         XA(1) = 1.0                                                    SMX    6
         XA(2) = 4.0                                                    SMX    7
         DO 13   I=1,3                                                  SMX    8
         FA(I)=XA(I)*SQRT(G/((1.+.5*G1*(XA(I)**2))**((G+1.)/G1)))-X     SMX    9
         SMX = XA(I)                                                    SMX    0
         IF(ABS(FA(I)) .LT. TOL) GO TO 32                              SMX   11
         IF(I.EQ.2) XA(3)=XA(1)-FA(1)*(XA(2)-XA(1))/(FA(2)-FA(1))      SMX   12
13       CONTINUE                                                       SMX   13
         X1SQ = XA(1)**2                                                SMX   14
         X1X2 = XA(1) - XA(2)                                           SMX   15
         X1X3 = XA(1) - XA(3)                                           SMX   16
         X2X1SQ = XA(2)**2 - XA(1)**2                                   SMX   17
         A = X1X3*(FA(2) - FA(1)) - X1X2*(FA(3)-FA(1))                 SMX   18
         A = A/(X1X3*X2X1SQ - X1X2*(XA(3)**2 - X1SQ))                   SMX   19
         B = (A*X2X1SQ - FA(2) + FA(1))/X1X2                            SMX   20
         C = FA(3) - A*(XA(3)**2) - B*XA(3)                            SMX   21
         Q = SQRT(B**2 - 4.0*A*C)                                       SMX   22
         SMX = (-B+Q)/(2.0*A)                                          SMX   23
         IF((SMX.LT.1.0) .OR. (SMX.GT.4.0)) SMX=(-B-Q)/(2.0*A)         SMX
         DO 31   I=1,5                                                  SMX   25
         SQ = SMX**2                                                    SMX   26
         F = SMX*SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))) - X           SMX
         IF (ABS(F) .LT. TOL)  GO TO 32                                SMX   28
         FP = 2.0*(1.0-SQ)*(SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))))/(2.0+ SMX  29
        1 G1*SQ)                                                       SMX   30
31       SMX = SMX - F/FP                                               SMX   31
32       RETURN                                                         SMX   32
         END                                                           SMX   33
```

```
      FUNCTION PR(G,A)
C   DETERMINES THE RATIO OF TOTAL PRESSURE TO STATIC PRESSURE AS A
C    FUNCTION OF MACH NO. AND GAMMA.   G=GAMMA,  A=MACH NO.
      G1 = G-1
      PR = (1.0 + 0.5*G1*(A**2))**(G/G1)
      RETURN
      END
```

ION   TR   CDC 6600 FTN V3.3-251A OPT=1   07/15/71

```
      FUNCTION TP(G,A)
C   DETERMINES THE RATIO OF TOTAL PRESSURE TO STATIC PRESSURE AS A
C   FUNCTION OF MACH NO. AND GAMMA.  G=GAMMA,  A=MACH NO.
      TR = 1.0 + 0.5*(G-1.0)*(A**2)
      RETURN
      END
```

```
CORE MAP   08.56.31.   NORMAL
           ---TIME---LOAD MODE  --L1--L2------TYPE----------------------------USER---++---CALL-------
           FWA LOADER  040764   FWA TABLES  035722
           -PROGRAM----ADDRESS-                          --LABELED---COMMON--
           MCMCRJ      000152                            CYCL        000100
                                                         BUMA        000110
                                                         AINLT       000113
           CYCLE       003511                            DUM         000135
                                                         CYCL        000100
                                                         BUMA        000110
                                                         AINLT       000113
           AINLET      004365                            DUM         000135
                                                         DUM         000135
                                                         BUMA        000110
           DUMP        004673                            AINLT       000113
           BUMAC       005005                            DUM         000135
                                                         BUMA        000110
           PROPAN      005036                            DUM         000135
           AIRTHR      005124
           ATMOS       005171
           ATKN        005363
           SOLNEW      005616
           X           006265
           Y           006310
           Z           006334
           FUELDAT     006350
           BUYIN       010010
           XM          010147
           YM          010371
           ZM          010570
           SMX         010766
           TR          011213
           PR          011231
           GETRA       011253
           SIOS        011272
           SYSTEM$     012646
           IFENDF$     013631
           INPUTC$     013719
           INPUTN$     014026
           KODER$      015205
           KRAKER$     016601
           OUTPTC$     020325
           ALNLOGE     020421
           EXPE        020460
           SQRTE       020524
           XTOYE       020546
           ----UNSATISFIED EXTERNALS-----
                                                                                      REFERENCES
```

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